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The Role of Black Soldier Fly, *Hermetia illucens* (L.) (Diptera: Stratiomyidae) in Sustainable Waste Management in Northern Climates

Luis Alvarez
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The Role of Black Soldier Fly, *Hermetia illucens* (L.) (Diptera:
Stratiomyidae) in Sustainable Waste Management in Northern
Climates

by

Luis Alvarez M.A.Sc., P.Eng.

A Dissertation

Submitted to the Faculty of Graduate Studies
through Civil and Environmental Engineering
in Partial Fulfillment of the Requirements for
the Degree of Doctor of Philosophy at the
University of Windsor

Windsor, Ontario, Canada

2012

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The Role of Black Soldier Fly, *Hermetia illucens* (L.) (Diptera: Stratiomyidae) in
Sustainable Waste Management in Northern Climates

by

Luis Alvarez

APPROVED BY:

Dr. Jeff Tomberlin, External Examiner
Texas A&M University

Dr. Sherah VanLaerhoven
Department of Biological Sciences

Dr. Paul Henshaw
Department of Civil and Environmental Engineering

Dr. Rajesh Seth
Department of Civil and Environmental Engineering

Dr. Edwin Tam, Advisor
Department of Civil and Environmental Engineering

Author's Declaration of Originality

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Abstract

This research assessed the feasibility of using Black Soldier Fly, *Hermetia illucens*, in cold weather climates to manage organic wastes. The goal was to determine if the flies could be kept alive year round in a controlled facility when exterior conditions turned inhospitable. A proof-of-concept experiment was undertaken by constructing a small research facility in Windsor, Ontario, Canada at the Essex Windsor Solid Waste Authority's Landfill Site inside two greenhouses. Although the data collected were highly variable, the experimental trials demonstrated that the design process was successful overall: *Hermetia illucens* can be propagated successfully in controlled environments in cold weather conditions.

Key design parameters were investigated, including the waste consumption rate per maggot per day and the waste application rate. These parameters were then used as a basis for the design of a prototype waste processing facility utilizing BSF as the treatment method. A mass balance of the relevant flows and a life cycle inventory was conducted as precursors to future life cycle assessments of this process.

A limited cost assessment was included to determine the economic feasibility of operating a BSF waste processing facility year-round in winter climates. The cost analysis revealed that the current design, under research conditions, could be economically viable and improvements to the process are necessary. These improvements include the more efficient use of electricity, water, natural gas and three dimensional waste processing via the use of aeration to the food pile.

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End Communication...

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Chapter 1 - Introduction

1.0 Introduction

The push for sustainability has produced many changes to common industrial and commercial processes. Private and public sectors alike have revised production policies to include environmental considerations, which in turn affect the manufacture, distribution and disposal of goods and services. Similarly, solid waste management has also undergone policy and technological changes to use contemporary scientific knowledge to achieve sustainability.

In this research, *Hermetia illucens* (L.) (Diptera: Stratiomyidae) or the Black Soldier Fly (BSF) is used as a waste management tool in a similar fashion to vermicomposting. There are significant additional benefits: BSF can process a wider variety of organic wastes and the larva are considered useful as a feed source for animals. BSF could also provide potential chemical precursors to producing biodiesel (Zheng et. al. 2012). BSF have been utilized for waste management purposes in lower latitudes where temperatures and sunlight are well suited for the propagation of the species year-round. In those studies, the BSF appear well suited to process organic materials. In colder climates the temperature daylight requirements are either not obtainable or are significantly reduced.

The location for this research was at Essex County, Ontario, Canada approximately 300 km south of the BSF's northern limit in their normal, outdoor environments. Although BSF thrive in the summer, winter temperatures will kill them so they must leave, find shelter during winter months or re-colonize every spring. Maintaining a colony in such inhospitable conditions would require infrastructure to ensure that environmental variables remain within tolerable levels. This research will determine if a controlled environment can successfully propagate the species at higher latitudes, and if so, how to conceptually design a waste system that uses BSF effectively. In addition, it will lay the groundwork for a sustainability assessment of the process and a comparison to current waste disposal practices for organic wastes.

In cooperation with the Essex Windsor Solid Waste Authority (EWSWA) and the University of Windsor's Biological Sciences department, a research facility and necessary infrastructure have been sourced, designed and constructed at the regional landfill to house and propagate BSF in a northern climate. It is the aim of this research to:

1. Explore the feasibility of using BSF to process organic wastes in cold climates;
2. Design a proof-of-concept system that can propagate the BSF in a contained environment in unfavourable climates;
3. Quantify material flows using a Life Cycle Inventory (LCI) and explore the potential for revenue from this process; and
4. Determine a relationship of the parameters that would affect the transition from the existing prototype to a full-scale facility capable of processing commercial or industrial quantities of organic waste from restaurants or food processing industries.

Chapter 2 – Literature Review

2.0 Literature Review

2.1 Solid Waste Management – Current Practices and Issues

Solid waste management has evolved considerably since the beginning practices of open dumping and burning. Current waste management practices include reduction, reuse, recycling and composting. The preceding however, are not final disposal methods; in waste management, landfilling and incineration are the most common final disposal methods (EPA 2008). The increasing societal demands for resource efficiency and sustainability have also produced new but not yet mainstream alternatives including pyrolysis and plasma gasification. The landfill remains the most common final disposal approach for non-hazardous, non-industrial waste – or common municipal solid waste (MSW).

Americans generated approximately 249.6 million tonnes (mt) of MSW in 2008 (EPA 2008). Recycling and composting diverted 82.9 mt of waste from permanent disposal, while combustion with energy recovery treated 31.6 mt of waste. The remaining 135.1 mt was delivered to landfills for final disposal. Canadian waste production totaled 34 mt in 2008 (Statistics Canada 2008). North American MSW in 2008 consisted of organic waste (food scraps 12.7%, wood 6.6% and yard trimmings 13.2%), paper & paper products 31%, glass 4.9%, metals 8.4%, plastics and textiles 7.9% (EPA 2008). Although landfills are the most common final disposal method for MSW, they can continue to pose technical, environmental and societal issues.

A modern landfill system consists of waste cells, each containing a liner to prevent leachate migration into the surrounding groundwater, a collection system for leachate, and landfill gas, monitoring equipment and, upon reaching capacity, a top capping layer to prevent infiltration. Cracks and leaks can sometimes form in the upper and lower liners, allowing for infiltration of water and the release of contaminants into the surrounding groundwater – improper construction hastens this scenario. Leachate

composition varies from landfill to landfill but can contain high values of chemical oxygen demand, ammonium, and toxic substances such as heavy metals that can complicate treatment options (Demirbas 2006).

Another by-product of waste decomposition is landfill gas, most notably methane, which can be reclaimed for use in energy production. Extensive infrastructure, in the form of collection piping, is required to collect the gas. The methane produced from landfills may also require processing to remove impurities for efficient energy recovery, further increasing recovery costs (Demirbas 2006). The gas is then pumped to an energy recovery facility and the resulting electricity is then distributed to consumers.

Fugitive emissions are also common at landfills, these can include dust, stray garbage, noise, and odours; these factors tend to make landfills an unwelcome neighbour making a new site selection a political event. The result is that a landfill can be located far from the waste generation sites increasing transport costs and CO₂ emissions from collection vehicles.

Landfills are also a large investment in terms of capital and time. The average active lifespan of a landfill ranges from 25 to 30 years but that number belies the fact that even after a landfill has stopped receiving waste, decomposition continues after the site closes. This causes a need to monitor the surrounding groundwater, surface water if present, geological site stability and potential gas migration. Despite these flaws, landfilling remains an indispensable technique for MSW management for the foreseeable future. Because cost competitive alternatives to landfilling are not yet widespread and the siting of new landfills is a politically charged event, a variety of waste diversion and waste reduction approaches attempt to extend the lifespan of existing landfills.

2.2 Organic Waste Composition and Diversion Techniques

In 2008 the most abundant component of MSW in the United States was the organic fraction consisting of food scraps, yard trimmings and wood (EPA 2008). These organic components represent a large amount of stored chemical energy, and mainly responsible for the production of biogas and leachate. Instead, if this portion of the waste stream could be partially or fully diverted from landfills and put to use on a significantly shorter time scale, landfill life spans could be increased and pollution issues stemming from leachate and gas production could be reduced.

Current diversion programs include the reduction of resource consumption, the reuse and recycling of a resource, and the composting of organics. The composting process plays the largest role in diverting organics from a landfill but it is limited; it cannot easily accept animal protein based wastes, it must be kept aerobic through manual or mechanical mixing, and nutrient ratios must be planned and maintained for a successful run. Composting diverted approximately 22.1 mt from landfills in 2008 (EPA 2008).

The time required to produce finished compost is highly variable and depends on the composition of the starting material, aeration frequency, proper nutrient ratios, moisture content and temperature. Finished compost can be obtained in as little as one week in mechanical composting operation to as long as six months in a static pile. In addition, the composting end product's uses are limited mainly to soil amending and erosion control applications. In an effort to overcome some of the limitations of traditional composting, organisms have been introduced into the compost pile. The most common adaptation is vermicomposting in which a worm species, such as the red wiggler (*Eisena foetida* or *Eisena andrei*), is added to the compost. The worm digests the wastes and produces castings; the castings are nutrient rich and can be used as a fertilizer or soil conditioner (Mitchell 1997).

2.3 The Black Soldier Fly

Another potential useful species is the black soldier fly (BSF), *Hermetia illucens*. It is considered a non-pest species native to North and South America ranging from 40 degrees north to 40 degrees south (McCallan 1974). The species is not considered a disease vector or a nuisance to humans (Furman et. al. 1959); however there have been reported cases of intestinal myiasis in humans (Lee et. al. 1995). Myiasis is the parasitic consumption of tissue by fly (Diptera: two-winged) larvae. These reports appear limited to cases where infection occurred in equatorial zones. The likelihood of disease transfer from BSF to humans in a waste management facility is not known, but with the use of adequate personal protective equipment, the incidence of such transfer is not expected to be significantly worse than current disease vectors present at a landfill.

The adult flies are not believed to congregate around human residences as a disease spreading organism (Furman et. al. 1959). This is mostly likely because studies suggest that the flies do not need to consume food during the adult phase of their life cycle (Sheppard et. al. 2002, Furman et. al. 1959) and this significantly reduces the opportunity to spread disease. Instead, the adults are pre-occupied with mating, egg-laying and when necessary, acquiring water.

2.3.1 Lifecycle and Physical Requirements

The BSF has five stages in its lifecycle: egg, larvae, prepupal, pupae and adult. These are shown in Figure 1.

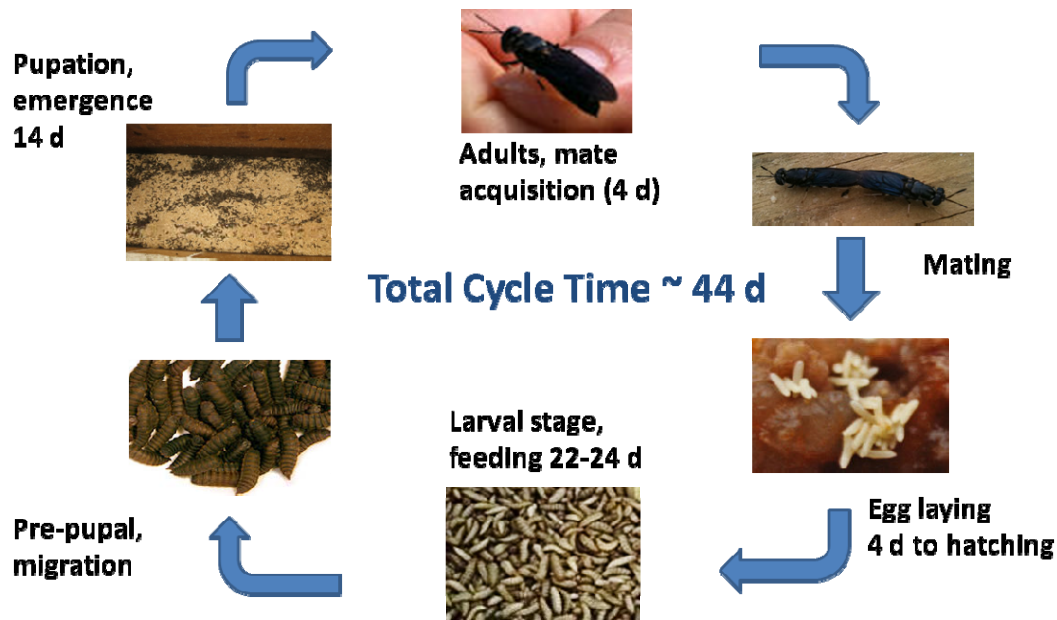


Figure 1 – BSF Life Cycle

The larval stage is further divided into phases called *instars*. An instar is defined as the period between each moulting of their exoskeleton. The number of instar stages varies for different fly species: *Hermetia illucens* has five instar stages. All of the adult fly's nutritional requirements are obtained during its larval stage and adult flies survive on their fat reserves obtained as maggots. When this fat reserve is depleted the adult dies (Myers et. al. 2008).

The larvae have a wide ranging diet: they can consume animal feces, rotten and fresh flesh, fruits, restaurant waste, kitchen waste, cellulose and possibly a variety of other organic wastes (Nguyen 2010, Holmes 2010, Sheppard et. al. 2002, Tomberlin et. al 2002). They have been observed to consume restaurant waste left at 30°C for 3 weeks contaminated with mould. However, the maggots appeared lethargic after doing so based on observations in this research.

Soldier flies, from egg to adult, have an estimated life cycle of 40 days but this length depends on the environmental conditions present and the rearing diet. Waste consumption rates appear to depend on the size of the maggot and the type of food being consumed (Diener et. al. 2009).

2.3.2 Larval Stage

Immediately after hatching the new nymphs seek a food source and begin to feed. The maggots do not sleep but they do not consume waste continuously. Optimal moisture content for the feed ranges from 60% to 90% (Myers et. al. 2008). Optimal temperatures for efficient food processing range from 27 to 33°C (Sheppard et. al. 2002). Lower temperatures are most likely tolerable because the maggots generate heat as they consume food through their writhing motions. The maggots secrete enzymes that make the food digestible prior to ingestion by liquefying the waste as they consume it. The moisture content of the resource is important as it affects BSF development. Moisture contents outside the optimum range will cause adverse effects. Too much moisture will force the maggots leave the food/resource matrix they are feeding in; and not enough will prevent efficient consumption (Fatchurochim et al. 1989). However, these moisture circumstances can be exploited to engineer a BSF waste management system: the moisture preferences of the larvae could provide a simple method to control and direct the maggot's location in the system.

- The feeding site can be kept moist, and a path to a drier area (pupation medium) can be provided to encourage migration to the desired location; and
- The development rate can be controlled, if required, by modifying the moisture content in the resource.

It also appears that soldier fly maggots secrete chemicals that warn other fly species that a food source colonized by soldier fly maggots is not an ideal egg laying site leading to effective reductions of the common housefly (Bradley and Sheppard 1983).

The nutrition source used in the larval stage can also affect adult fly characteristics (Tomberlin et. al. 2002). Thus in a full scale waste processing facility the nutritional content of the incoming waste stream may need to be monitored to ensure that the larvae are eating a balanced diet. This would be important because the facility would require healthy adults to maintain egg production at required levels.

2.3.3 Migration and Pupation

Prior to reaching the pupation stage the larva will leave the feeding site to find an adequate pupation site. Once the larvae have consumed enough food they begin to migrate away from the food source (Sheppard et. al. 1994). If the maggots that are ready to pupate can be directed to a location selected by a human operator, then the pupae are effectively harvesting themselves. The maggots have entered a wandering stage searching for a drier and darker location than the feeding site to continue their life cycle. Successfully exploiting this instinct means that no additional effort is necessary to remove them from the feeding site. Maggots have been shown to migrate considerable distances in order to find an adequate pupation site.

The maggots will also change colour, a circumstance that could be exploited to further sort them for quality purposes. However, the maggots are accomplished burrowers and can enter small spaces and crevices with ease and when they are wet they can attach themselves to a wide variety of surfaces including plastics, wood, rubber and metals. This can pose problems trying to contain them in specific feeding areas.

The time spent by each maggot in the migration stage varies but appears to be dependent on the maggot's ability to locate an ideal pupation site. A study suggested that the maggots favour drier conditions for a pupation site but require ambient humidity levels of approximately 60% to emerge as adults (Holmes 2010, Sheppard et. al. 2002). Migrating maggots are suspected of leaving chemical trails that other maggots follow creating a migration path.

Another characteristic of an ideal pupation site is protection from predators and unfavourable environmental conditions, such as flooding. The pupation media itself should be porous and loose to allow for easy burrowing of wandering maggots. A medium with these properties should also provide adequate oxygen levels so the pupae can breathe. If the pupation medium is too fine the spiracles, or breathing structures, can become clogged possibly resulting in death.

The depth of the pupation medium is also important. If it is too deep, the emerging flies will fail to reach the surface. If it is too shallow, the maggot may not deem the location adequate and continue to wander, wasting its fat reserves thereby reducing its harvest value or its chance to successfully mate. Wandering maggots have been shown to pupate without a pupation medium if no suitable medium is present (Holmes 2010). Studies have shown the ideal depth for a pupation medium is 15 to 20 centimeters. Pupation can last five to seven days depending on temperature and ambient humidity.

2.3.4 Adult Stage and Egg Laying

Mating typically occurs two days after emergence from the pupal stage to the adult stage. Temperature and ambient light levels are important in order for the flies to initiate mating. An unpublished study by Zhang et. al. (circa 2009) reported that a minimum irradiance of 70 micromoles/m²/s is necessary to achieve mating; the peak numbers of mating pairs were observed at 100 micromoles/m²/s. Other literature sources suggest an irradiance of over 200 micromoles/m²/s is optimal (Sheppard et. al. 2002). These figures have been disputed by an unpublished source to be much higher, possibly in excess of 500 micromoles/m²/s. There is limited data available on what specific wavelength or ranges of wavelengths are responsible for the initiation of mating and what time exposure is necessary. All of the studies reviewed showed that mating levels of adults were highest under natural sunlight: the use of artificial lighting should therefore be considered supplemental when natural sunlight exposure is not adequate.

BSF mating begins in the air with aerial questing after stimulation by light (Furman et. al 1959). Aerial questing is thought to be an important aspect of the mating process, and any facility should have enough air volume to facilitate this event; however, no recommendation on volume and adult fly densities were found in the literature. Egg laying usually occurs two days after mating. Females seek out an area that is close to a food source to deposit their fertilized eggs. The mechanism for this action is believed to be the detection of volatile chemicals from rotting wastes (Sheppard et. al. 2002).

Females will also leave chemical markers that attract other females to a suitable egg laying site. Females prefer not to lay eggs directly on a food source but near it.

The ideal egg laying site should be maintained at 27°C with an ambient relative humidity of 60% or more: at these conditions egg hatching rates of 80% or more have been observed (Holmes 2010, Sheppard et. al. 2002).

In the majority of the studies reviewed where BSF colonies were reared, the egg laying and waste processing activities were conducted in separate locations. Eggs were collected in the corrugations of cardboard, or flutes, and then transferred to the testing apparatus. This is done because eggs are fragile, small and vulnerable to changes to environmental variables; the flutes provided protection for eggs and encouraged the female's ovipositor to lay eggs in the confined space. In a waste management facility, it would be preferable to automate or remove the need for egg handling.

2.4 Waste Management Applications

The use of BSF for waste management is not new. BSF maggots have been used in agricultural settings to stabilize problematic wastes including, swine, bovine and poultry manures in climates that sustain BSF year round: these settings include a large chicken farm house, pig farms and cow farms (Sheppard and Newton 1994; Axtell 1999). The BSF's ability to digest other wastes including the organic portions of MSW, wastewater treatment sludge and fish rendering wastes has been studied by other researchers. However, there are significant questions, such as: what are the optimum feed rates? This question is actually quite complex: the optimum applied rate depends on the food source and the age of the maggots because BSF maggots consume different wastes at different rates at different instar phases.

In a study conducted by Nguyen (2010), five different diets, fish renderings, liver, fruits and vegetables, poultry feed and restaurant wastes were fed to different maggot groups. Each diet was shown to have a different waste consumption rate and the rate increased as the maggots increased in size.

Diener et. al. (2009) studied the consumption rates of various organic municipal solid wastes. Their goal was to determine the maximum amount of waste (dry mass) that BSF maggots could process in a day while maximizing dry biomass production. Two-hundred, six day old larvae were fed differing rates of various wastes. Quantitative nutritional aspects were based on the terminology outlined in Slansky and Scriber (1981). The following quantities were defined by Slansky and Scriber:

- B – the biomass that was gained (measured by Diener et. al. as the increase in pupae mass);
- I – the total food offered;
- F – the residue leftover in the containers (includes undigested food and excrement);
- M – the ingested food that was incorporated into biomass (calculated by mass balance in Diener et. al. (2009));
- AD – how much of the ingested food is digested; and
- ECD – how efficiently digested food is converted to biomass.

The values are related in the following fashion, with higher ECD values indicating a high food to biomass conversion efficiency.

$$B = (I - F) - M \text{ and } ECD = \frac{B}{(I-F)}$$

Diener et. al. 2009 used these values, along with a reference food source, to estimate the amount of a waste type that could be added to a given areal density of maggots. In their study, Diener et. al. (2009) predicted that a feeding rate of 100 mg of chicken feed with 60% moisture (the reference food source) per maggot yielded the optimum trade-off between nutrient rich prepupa and high waste consumption in the shortest time span. In essence, Diener et. al. (2009) calculated an optimal feed flux for BSF maggots for a given waste type. The flux was defined as the mass of waste applied to a given area containing a fixed number of actively feeding maggots in a day (kg/d/m²).

The actual calculations used to obtain the conversions were not described in the paper and the results obtained depend on a variety of factors including the fiber content of feed, moisture content of feed and ambient temperature. Diener et. al. (2009) did not calculate the AD variable in their study (as suggested by Slansky and Scriber (1981)) which may have affected the accuracy of their estimates; nevertheless, the projected conversion rates for additional waste types serve as useful starting points for operating a waste processing facility using BSF maggots.

The estimates proposed by Diener et. al. (2009) are listed below for various feed sources. The table assumes a maggot density of 5 larvae/cm² but does not mention the age of the maggots.

Table 1 - Waste Loading Rate – adapted from Diener et. al. 2009

Waste Type	Daily Feeding Rate (mg/larva/day)	Waste Loading Rate (kg/d/m²)
Chicken Feed	100	5.00
Kitchen Waste	61	3.05
Vegetable Waste	98	4.90
Green Banana	103	5.15
Pig Manure	158	7.90
Poultry Manure	175	8.75
Human Faeces	130	6.50

In a study conducted by Sheppard (1994) BSF maggots were used to stabilize the manure of approximately 460 cage hens. The maggots were able to convert chicken manure into a feedstuff, larval mass, containing 42% protein and 35% fats. House fly breeding was eliminated and manure mass was reduced by 50%.

In another study conducted by Myers et. al. (2008), BSF maggots were used to stabilize dairy manure in a controlled laboratory setting. BSF larvae were fed four different rates of manure to assess their development. Interestingly, the feed rate affected the development of the larvae: the larvae that received less manure did not weigh as much

as their overfed counterparts and the adults of the underfed larva lived three to four days less. However, the larvae that were fed less manure turned out to be more efficient at reducing manure dry matter.

Myers et. al. (2008) observed that larvae fed 27 g of manure daily reduced dry matter by 58% whereas the other test subjects, receiving 70 g of manure per day, reduced dry matter by only 33%. There was also a higher incidence of mortality (29%) among larvae that were fed 70 g of manure when compared to the test groups fed 27 g and 54 g (<20%). Myers et. al. (2008) also found that the phosphorus content of the manure was reduced by 61% to 70%, and the nitrogen content was reduced by 30% to 50% respectively, across all treatments.

In all of the reviewed studies, BSF maggots were shown to have significant beneficial effects towards reducing dry waste mass further substantiating BSF's potential as a waste management agent.

2.5 Potential Uses for BSF Maggots/Prepupae

In addition to being voracious consumers of organic wastes, BSF maggots contain useful organic compounds that have commercial and industrial value: these include¹:

- 42.1% Crude protein
- 34.8% Lipids
- 7.0% Crude fibre
- 7.9% Moisture
- 1.4% Nitrogen free extract (NFE)
- 14.6% Ash
- 5.0% Calcium
- 1.5% Phosphorus

¹<http://www.esrint.com/pages/bioconversion.html>H; Based on a diet of “fresh restaurant food waste”

The larval excretions and pupae casings can be used as a replacement for peat moss but unlike peat moss, the casings and excretions could easily be renewable resources. The maggots have been used as a substitute for dairy, swine and poultry feeds. In this role the BSF maggots both stabilize problematic wastes and create a value-added agricultural product.

The maggots have also been fed to aquaculture systems – an industry facing a potential shortfall of feed protein. Global aquaculture systems produced 45% of all the seafood consumed in the world in 2007 and their production is expected to increase to 75% in the next twenty years (Papadoyianis 2007). In order to maintain this growth, fishmeal production must increase accordingly. However fishmeal is not only used to supply the aquaculture industry but other animal husbandry industries as well. Cattle, poultry, swine and mink producers all use fishmeal as the primary protein source for their animal diets (Papadoyianis 2007).

Eighty percent of the world's fishmeal supply is produced by 10 countries and 3 of these countries are net importers of fishmeal. Twenty-five percent of the global fish production is used to produce fishmeal and fish oil. Because the production of fish is geographically isolated, every tonne of fishmeal is transported an average of 5000 km before reaching the consumer (Papadoyianis 2007). In addition, world fish stocks are in decline. All of these circumstances could contribute to a shortage of fishmeal that would inhibit the growth of the aquaculture industry. The nutritional makeup of BSF maggots could allow them to provide an alternate protein source for animal husbandry industries (Papadoyianis 2007).

BSF maggots have the ability to incorporate fats from their diet into their chemical composition. In a study conducted by St. Hilliare in 2007, BSF maggots were used to stabilize cow manure. The maggots were to be used as a feed for a trout aquaculture industry. BSF maggots are low in omega-3 and omega-6 fatty acids but when the manure feed was combined with fish offal from a rendering plant, the BSF's omega-3

and omega-6 fatty acid content increased (St. Hilliare 2007). This suggests that BSF larvae can be customized to provide a nutritional profile to suit a specific dietary need.

The potential benefits of mass production of BSF maggots for use as a waste management agent and protein source have been illustrated in several studies. Most of these studies occurred in lower latitude areas with above freezing temperatures year round. BSF stabilization of waste appears to be a useful approach in these regions. However, with even more northerly communities facing increasing solid waste management challenges, could a BSF waste management facility operate at northern latitudes where unfavourable environmental conditions exist for a majority of the year? Although these limitations could be overcome with the use of technology, it is unknown if this process would be a notable improvement over current waste management practices. The literature to date does not compare BSF oriented alternatives against other waste management practices.

2.6 Performance Evaluations – LCA and BCA

Alternatives can be compared to each other using techniques such as a life cycle assessment (LCA) and a benefit cost analysis (BCA). Each approach delivers different information and has differing scopes. For the purposes of this research the established BSF production facility will be evaluated using the LCA and BCA approaches.

2.6.1 Life Cycle Assessment

The LCA approach was developed as an analytical tool to assess the environmental impacts from products, processes, policies or services. The development of the methodology began in the USA in the 1960's to early 1970's (Hauschild et. al. 2005). The original studies focused on the environmental impacts from different types of beverage containers (Hauschild et. al. 2005). In the 1990's four standards were developed for LCA and its main phases: they were issued by the international standards organization (ISO) under the ISO-14000 series of standards for environmental

management (Hauschild et. al. 2005). The harmonization provided by the ISO standards increased the credibility of results enabling the widespread use of LCA in industrialized countries in Europe, North America and Asia.

The LCA approach typically consists of the following stages (Hauschild et. al. 2005):

- Goals and scope definition;
- Life Cycle Inventory;
- Life Cycle Impact Assessment; and
- Interpretation and Corrective measures.

The LCA is performed as an iterative process and it is possible that each stage maybe revised several times before the LCA is completed. With each iteration the uncertainty in the assessment is typically reduced. The process is considered complete when the uncertainty is reduced to a level where the initial questions posed in the goals and scope definition stage can be adequately answered. This does not imply that the assessment is all-encompassing, only that the questions posed at the beginning can be reasonably answered. The LCA approach will be used to determine the environmental impact of a BSF facility operating in cold climates.

To assess the economic viability of the proposed system, a BCA will be conducted to compare it against alternative disposal options for organic wastes, specifically landfilling and composting. The methodology outlined in the *Canadian Cost-Benefit Analysis Guide* 2007 will be followed as applicable. The results of the BCA will be used to determine the economic feasibility of the BSF waste processing system in northern climates. The combination of the LCA and BCA approaches will provide a reasonable comparison of the BSF waste processing system's performance when compared against existing disposal options.

2.7 Summary

Hermetia illucens larvae are voracious consumers of organic matter and data indicate that dry waste reduction values are in the vicinity of 50%, depending on the waste. The digested waste residue from BSF larvae has been used as a replacement for compost and has sufficient nutrients levels for use as a fertilizer and a soil amendment. The maggots themselves are suitable substitute for feed in animal husbandry operations.

BSF have been used in waste reduction facilities in warm climates to successfully consume organic wastes and as a feedstock. Waste consumption rates vary by waste type, moisture content, number of maggots present, size of the maggots present and temperature. Maggots will actively leave the feeding site and change colour when nutritional requirements have been met so that they harvest themselves. Year round cold weather operations were not encountered in the literature.

Successful mating by adult flies seems to depend on several factors, the intensity of light present, the length of exposure to the light, and most likely different wavelength ranges from the electromagnetic spectrum. Adult densities in the mating space may also play a role. A suitable egg laying site must protect the eggs from desiccation.

To preserve the continuous nature of the BSF life cycle, the infrastructure subsystems must be linked to the proceeding and preceding life stages while maintaining optimal ambient conditions. Optimal ambient conditions for all life stages range from 27°C to 33°C and at least 60% relative humidity. A minimum light intensity of 100 $\mu\text{mol}/\text{m}^2/\text{s}$ is required to initiate mating in adults.

It is the intent of this research to design infrastructure to propagate the species *Hermetia illucens* year round in cold climates by designing subsystems to contain life cycle stages, outline a facility design based on the waste consumption rate of the maggots and lay the groundwork for a sustainability assessment of the facility.

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Chapter 3 – Mass Balances

3.0 System Study Synopsis

The approach and methods used in this research involved a number of iterative steps and experiments in order to establish a basic understanding of what was involved in developing a proof-of-concept BSF-based waste management facility. This section provides a brief synopsis of the major phases of the research to help clarify what was done.

During the early stages of the research, the investigation focus was on developing the conceptual design and constructing a working model as a basis to establish a colony. After start-up problems were addressed and a colony could be maintained, the next step was to develop an approach to determine system parameters that could serve as the foundation for the design of future systems.

The larval stage of the organism's life cycle was designated as the starting point for the system design. This choice was made based on the reasoning that the waste consumption rate of the larvae would determine how much waste a facility could process, which in turn would determine the size of the reactor vessel(s) where the waste would be consumed. Furthermore, quantifying the mass and number of larvae that successfully migrated out of the reactor space was necessary to determine the reactor's productive outputs. These outputs would become inputs for the next stage of the flies' life cycle thereby affecting the design of adult space's infrastructure.

The most important measurable design parameter was the average dry matter consumption rate: the approach used to measure it was direct sampling of actively feeding maggots. Other necessary values were not so easy to measure. The most cumbersome was reliably measuring the number of adults present in the adult space. Attempts were made to count the adults using a modified version of the maggot sampling protocol but this approach eventually proved unreliable because of the high degree of mobility exhibited by the adult flies.

A satisfactory approach based on direct counting was ultimately not developed: any such approach would likely be affected by the same problems that made the original approach unreliable because of the adults' mobility. The method eventually used to estimate adult fly number was an indirect approach via the mass balance experiments and experimentally determined physical properties of eggs and adults.

The mass balances for the entire operation are presented first because the mass balance is the source for key design parameters of the adult space and its presentation will clarify the methods used in later parts of this thesis.

There were two balances done on two different materials in an attempt to quantify flows: 1.) a dry matter balance, and 2.) a water balance. The first set of balances was done on the reactor space (RS) and the second on the adult space. Raw data collected from experiments can be viewed in Appendix A.

The study of the system was divided by infrastructure versions and modes of operation. Three versions, defined by major overhauls to subsystems, existed at the landfill site and each was evaluated for performance. During the first two major system versions the facility was operated continuously: the life cycle of the flies was not interrupted and multiple generations existed in the facility at any given time. After the last major system revision, the facility operated in batch mode: only one generation was present in the system at any given time.

After the system was studied by version, an overall analysis of the aggregate data was undertaken to obtain averages of the necessary parameters for the design of a full scale facility. The calculations and methodology used to conceptually design a full scale facility were then determined and a process for its design is presented.

In an attempt to identify resource consumption, and to take the first step towards conducting a life cycle assessment of the process, a life cycle inventory was carried out. Material and energy flows were identified and quantified where possible. In addition,

potential environmental impacts from a full scale facility are identified. The research methodology approach is outlined in Figure 2.

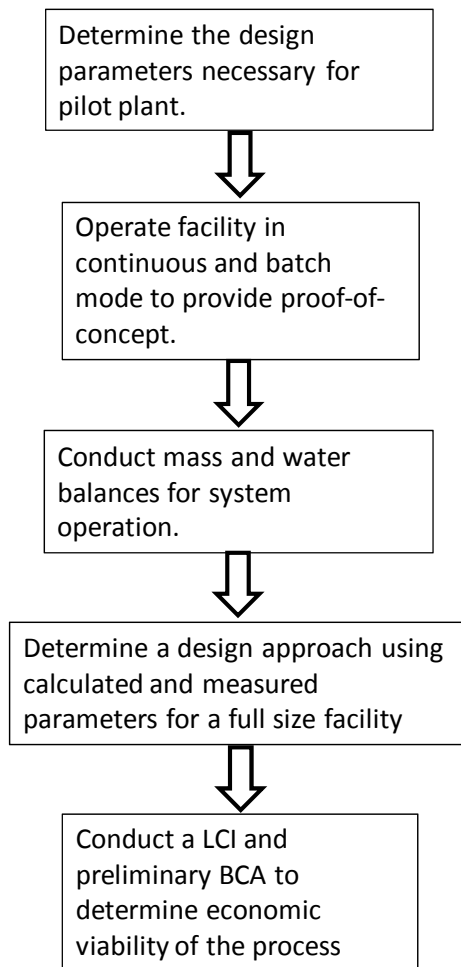


Figure 2 - Research Methodology Flowchart

3.0.1 Methods

The experiment to determine the mass balances consisted of six trials lasting thirty-seven days. Although these trials were conducted after the initial experiments at the landfill facility, the mass balance results are presented first because they establish the overall flows of the system. Establishing the mass balance at the landfill facility proved difficult because of the physical setting. Instead, the experiments were conducted at University of Windsor in the greenhouse of the biology building where conditions were similar to those at the regional landfill greenhouse (29°C to 45°C and 20% to 65%

humidity), but were significantly more controllable. The maggots were ordered from the *Phoenixworm Store*, Georgia, USA.

In each of the six trials, 1000 live BSF maggots were weighed (Precisa Model #BJ100M) and fed a diet of commercial chicken feed mixed to 70% water and 30% dry solids by mass. Each trial was kept separate in its own container. Chicken feed was used because of complications with acquiring a reliable amount of restaurant waste, which was the diet used for the main set of experiments. The effect this deviation would have on the results was not considered significant because data from Nguyen (2010) suggested that the maggots consume the different wastes in similar quantities. Restaurant waste was used in all other experiments.

The initial mass of the wet feed was measured and the trials were placed in an incubator at 29°C and 85% relative humidity. The trials were fed three times following the same procedure as the initial feeding.

The wet mass of the leftover waste residue was measured after all the feeding episodes were complete and the maggots had consumed all the waste. The feed was considered stabilized to waste residue by visual inspection. Moisture samples from the waste residue were collected from all six trials to establish an average to determine dry waste masses; they were dried in an oven at 110°C for 24 hours. When the majority of maggots were visually observed to turn dark (prepupa) they were separated from the remaining waste and their mass was measured.

The prepupae were then placed into vessels that contained a pupation medium, wood chips, and allowed to pupate. The vessels were then set in a cage to contain adults along with a food source outfitted with egg laying sites, plastic cardboard flutes. The cages were located in a greenhouse where the temperature and relative humidity were maintained between 27°C and 33°C (optimal) and 25% to 50% (not optimal but achievable). The humidity was lower than optimal conditions because of difficulties humidifying the greenhouse.

Egg laying was allowed to proceed for eight days (selected from observations during the operational experiments) for each trial after which the eggs were collected and their wet mass was weighed. The remaining pupal casings were sorted and weighed and these data were used to estimate the number of adults that were present in each adult cage. Eighty-four dried out intact adult carcasses were collected from the six cages and their masses were measured to determine an average dry adult carcass mass. This value was then used to estimate the number and mass of adult carcasses present in each cage.

The water balance was obtained from data collected from the material balances. The moisture content of all the materials was determined from moisture samples or from measurements when it was introduced into the system boundary when dry matter was mixed with water.

3.0.2 Results and Discussion

The dry material flows for the reactor and adult space are illustrated in Figure 3. The reactor space is the location where the maggots are actively feeding and the adult space is the location where the adults are flying, mating and laying their eggs. Standard deviations are presented in Table 2.

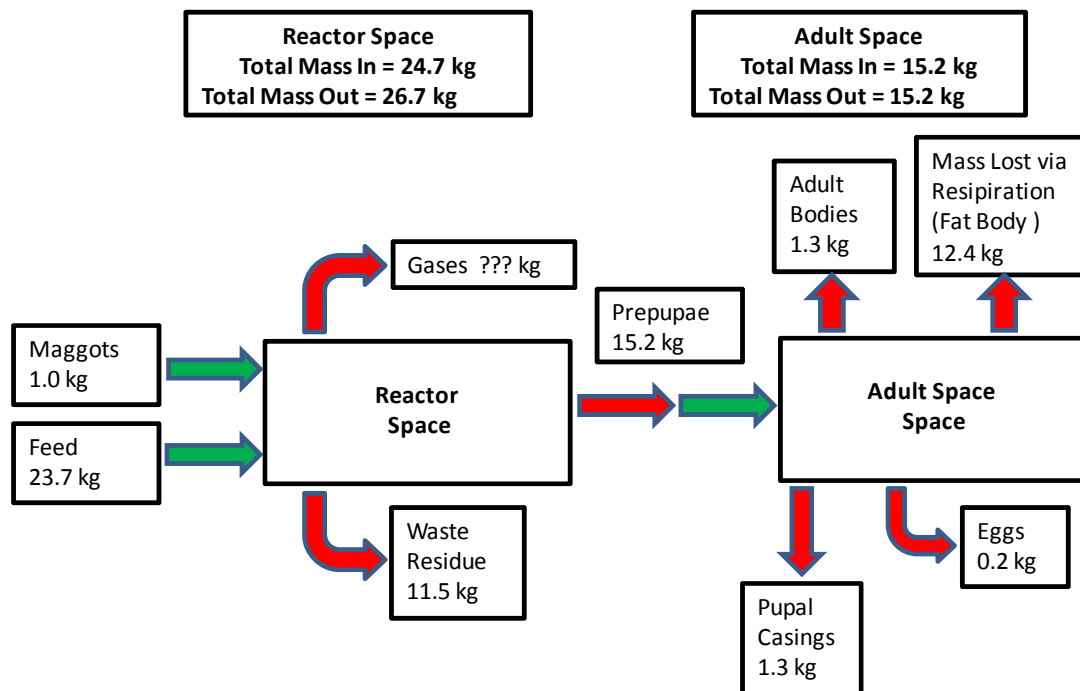


Figure 3 – Dry Material Balance

The composition and mass of the emitted gases was not determined experimentally during this research and an estimate could not be obtained via the mass balance: the expected constituents include volatiles, ammonia, and water vapour.

The water flows in the reactor and adult spaces are presented in Figure 4. Only water carried by the prepupae was considered in the balance because it is the only component that is not expected to vary from operation to operation making the adult space a subset of the reactor space. Water added to the adult space via the humidifiers and the misting system will vary depending on environmental conditions and was thus not considered.

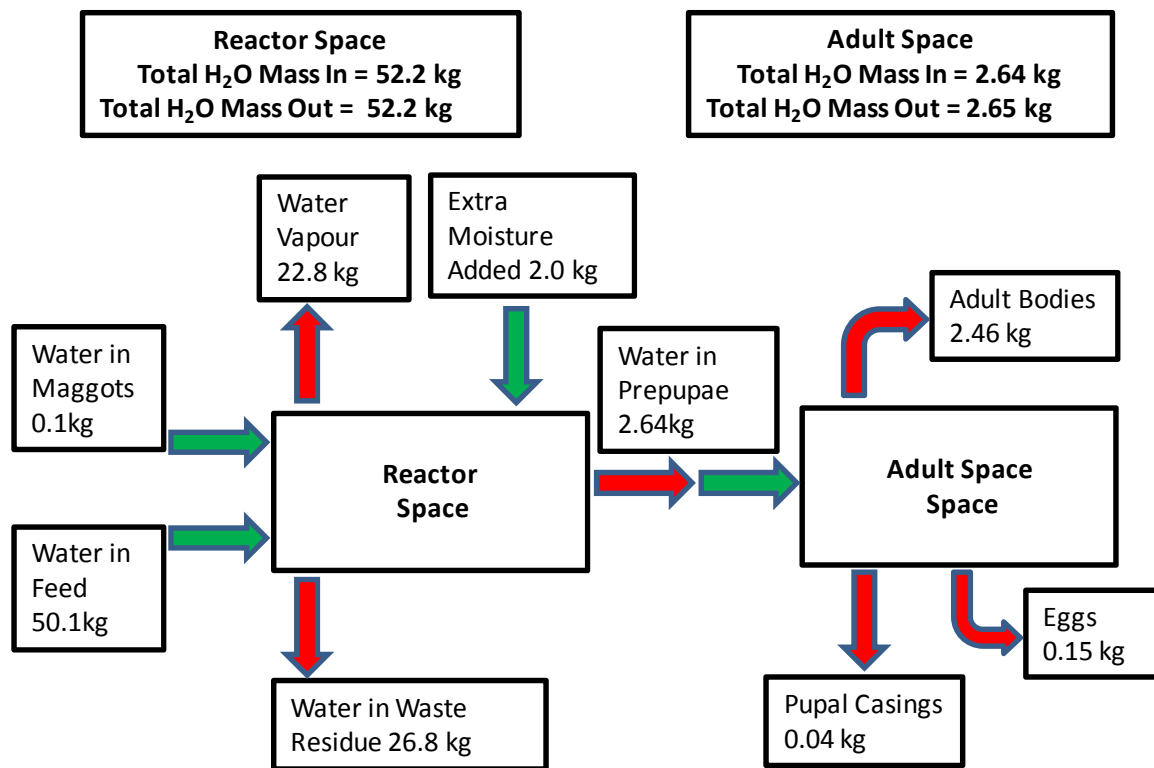


Figure 4 - Water Balance

Two of the flows were not determined by experimentation but through the mass balance calculations. The first was the amount of water that leaves the reactor as water vapour; this flow was assigned the remaining mass after all other flows were balanced.

The second flow was the moisture that left the adult space with the adult flies. Live adult moisture samples were not collected; instead the amount of water leaving the adult space with the adults was determined by an overall difference during the mass balance. Although extra water was added during the feeding stage to maintain adequate moisture levels, no free or ponding water was observed in any of the six experimental repetitions: it is assumed that there is no outgoing wastewater from the feed source. This is consistent with the main operational experiments where water from the reactor was recycled.

The mass of the pupal casings obtained during the experiments was considered a dry mass because moisture samples collected revealed that an insignificant amount of

moisture was present, approximately 3%. Ten pupal casings were collected after egg laying was completed and set to dry above a heat source for 48 hours; an oven was not used because there was possibility of burning the pupal casings. The data are presented in Table 2 along with their standard deviations to illustrate the variability. The variability in the amount of waste fed to the maggots is the result of feeding on a demand basis.

Table 2 - Material Balance Data, 6 trials with 1000 maggots per trial

Maggot Data	Parameter	Stdev
Average Packing Mass with Maggots (g)	45.6	5.5
Initial Average Wet Mass of 1000 Maggots (g)	14.5	5.5
Final Average Wet Mass of 1000 Maggots (g)	442.3	12.6
Moisture Content of Maggots (dec)	0.08	
Moisture Content of Feed (dec)	0.68	
Extra Moisture Added to Feed (g)	26.4	
Initial Average Dry Mass of 1000 Maggots (g)	13.4	0.7
Final Average Dry Mass of 1000 Maggots (g)	203.5	11.6
Moisture Content of Pupal Casings (dec)	0.03	0.02
Reactor Space Data		
Average Wet Mass of Feed Given (g)	994.2	155.6
Average Wet Mass of Collected Waste (g)	512.8	71.2
Average Moisture Content of Waste (dec)	0.70	0.03
Average Dry Mass of Feed Given (g)	317.7	49.8
Average Dry Mass of Waste Collected (g)	154.3	21.9
Average Wet Mass of Feed Consumed by Maggots (g)	481.3	103.9
Average Dry Mass of Feed Consumed by Maggots (g)	163.4	29.5
Average Dry Matter Reduction (%)	51.4	
Adult Space Data		
Average Wet Mass of Pupal Casings 100% Emergence (g)	17.3	4.1
Average Dry Mass of Adult Carcasses 100% Emergence (g)	17.2	4.1
Average Wet Mass of Eggs Collected (g)	3.7	0.9
Average Dry Mass of Eggs Collected (g)	1.7	0.2
Moisture Content of Eggs (dec)	0.54	
Per 1 kg of Maggots Introduced into Reactor		
Conversion Factor to 1 kg	74.7	
Initial Dry Mass of Maggots (kg)	1.0	0.0
Average Dry Mass of Feed Given (kg)	23.7	3.7
Average Dry Mass of Waste Collected (kg)	11.5	1.6
Average Dry Mass of Feed Consumed by Maggots (kg)	12.2	2.2
Final Average Dry Mass Maggots (kg)	15.2	0.9
Average Dry Mass of Pupal Casings 100% Emergence (kg)	1.3	0.3
Average Dry Mass of Adult Carcasses 100% Emergence (kg)	1.3	0.3
Average Dry Mass of Eggs Collected (kg)	0.1	0.0
Water Content of Each Component per 1 kg of Maggots		
Initial Mass with Maggots (kg)	0.1	0.0
In Feed Given (kg)	50.5	7.9
Water Vapour Leaving (kg)	23.2	8.7
Waste Collected (kg)	26.8	3.7
Feed Consumed by Maggots (kg)	24.5	5.3
Final Mass of Maggots (kg)	2.64	0.1
Pupal Casings 100% Emergence (kg)	0.04	0.0
Adult Carcasses 100% Emergence (kg)	2.46	0.1
Eggs Collected (kg)	0.15	0.0
Extra Moisture Added to Feed (kg)	2.0	

The established material flows were used in later analyses when collected data was not sufficient to characterize mass flows. Carbon and nitrogen balances were not conducted.

3.1 Introduction – Experimental Setup and Design for Landfill Operations

The black soldier fly (BSF) is being extensively assessed to determine its benefits for the fields of sustainability, waste management and aquaculture protein production. The voracious and undiscerning appetite of the BSF maggot coupled with the benign interaction the species has with humans (when it occurs) makes it a potentially ideal biological instrument in such fields. Processes designed around the BSF to stabilize organic wastes and produce a value added resource have succeeded in many locations where the climate is favourable for the year-round propagation of the species. However, similar installations in northern climates would face technical hurdles as they relate to abiotic factors due to much colder climate conditions.

3.1.1 Purpose

This research focused on whether or not the life cycle of the BSF could be exported to climates where the species could not propagate itself year round without technical assistance. One of the goals was to design a facility that could contain the entire life cycle of the BSF with minimal human labour inputs and yield viable future generations of the species. The research would also identify and quantify useful design parameters and materials that would aid in the design of future systems including: the mass loading rate, maggot yield, waste conversion rates and the harvesting capacity for the system.

Because a key aspect of this research is to demonstrate “proof-of-concept”, a prototype system for supporting the life cycle of the BSF was developed and refined through successive experimentation. Three system versions were operated at the EWSWA facility. The results are presented first by system revision to show the design progression and, the results are then reviewed as a whole. A fourth revision was constructed for operation at the University of Windsor. Raw data from all experiments at the landfill can be viewed in Appendix B.

3.1.2 Approach

The different stages of the black soldier fly's life cycle were used as a guide to conceptualize and then develop the facility's components. The life cycle of the BSF was divided into the following stages for subsystem design purposes and do not necessarily define the life cycle in a strict biological sense.

- The larval feeding stage;
- The migration stage;
- The pupation stage;
- The adult stage; and
- The egg laying stage

Each life cycle stage would be contained within a subsystem, and each subsystem would be connected to the previous and proceeding stage to encourage the continuity of the BSF's life cycles. Although the current system is the result of three major revisions and some minor adjustments, the continuity of the BSF as a functioning "unit operation" was clearly observed.

3.1.2.1 Operational Modes

The BSF system was run in two modes: continuous operation and batch operation. In the continuous operation mode, the life cycle of the BSF was allowed to progress from one life stage to the next without interruption or major cleaning in between generations (cohorts). This eventually led to a situation where multiple cohorts were present in the system at any given time so that multiple life stages (adults, larvae and eggs) were present all at once. It was also hypothesized that if a self-perpetuating colony could be established under the experimental conditions, it would demonstrate proof-of-concept for a BSF facility.

3.1.3 Cycle Definition

The complete biological cycle of the BSF encompasses the egg, larval, pupal, and adult stages. For the purposes of study cycles were referenced to the feeding stage - the start date of a new cycle would correspond with the addition of new maggots or the presence of freshly eclosed maggots and would end when the outward migration of prepupae was completed. In the continuous operation mode, establishing the start of a cycle was difficult because freshly eclosed (hatched) maggots were hard to locate. To compensate for this situation the start date was chosen three days prior from the first visual observation of newly eclosed maggots for every cycle, unless the reactor was re-started and the start date was actually known. The end of a cycle was identified when a substantial portion of prepupae, a migration wave, were observed to exit the reactor space: this was determined by visual observation.

In the batch operational mode, only one cohort was present so that only one life stage was present at any given time. The continuous mode was operated first for eight cycles followed by the batch mode which lasted four cycles.

3.2 System Version 1 – Continuous Operation Sept 30, 2009 to Mar 29, 2010

3.2.1 Infrastructure Description

The facility was located at the Essex County regional landfill in cooperation with the Essex Windsor Solid Waste Authority. The research was conducted inside an 82.8 m³ rectangular inner greenhouse located inside a 1500 m³ semicircular shaped outer greenhouse with an approximate area of 348 m². The inner greenhouse contained a forced air natural gas furnace to provide heat in the winter and a 0.762 m diameter fan to ventilate the inner greenhouse in the summer.

The outer greenhouse was not heated in the winter but it contained a ventilation fan and louvers to provide air cooling in the summer time. A direct water supply was not

available so water was pumped into a 1.14 m³ cylindrical tank that was filled once it reached a preset minimum level, approximately half volume. A 550W (¾ H.P.) motor and pump were used to supply water to the grinder and the misting pump.

A Fogco™ model # 92501, 1.7 MPa (250 psi) mister was used to supply water to the reactor space and the adult space. This was the sole water delivery system for this system revision. A 3-phase 208V, 2200W (3 H.P.) electric food grinder was used to grind organic waste into a slurry to homogenize the waste and reduce the potential for pest attraction. The waste fed during the startup phase between September and December of 2009 was a mix of restaurant waste, fish renderings and fruits and vegetables. However the diet was simplified at the start of January 2010 when franchise restaurant waste, consisting of carbohydrates, proteins and fats, was the only feed used in further operational cycles. This system version spanned two complete generations of BSF or cycles 1 and 2.

The inner greenhouse was divided into two volumes: one housed the feeding space, pupation trough and preparation area, while the other contained the adult space and hatchery. The layout is illustrated in Figure 5.

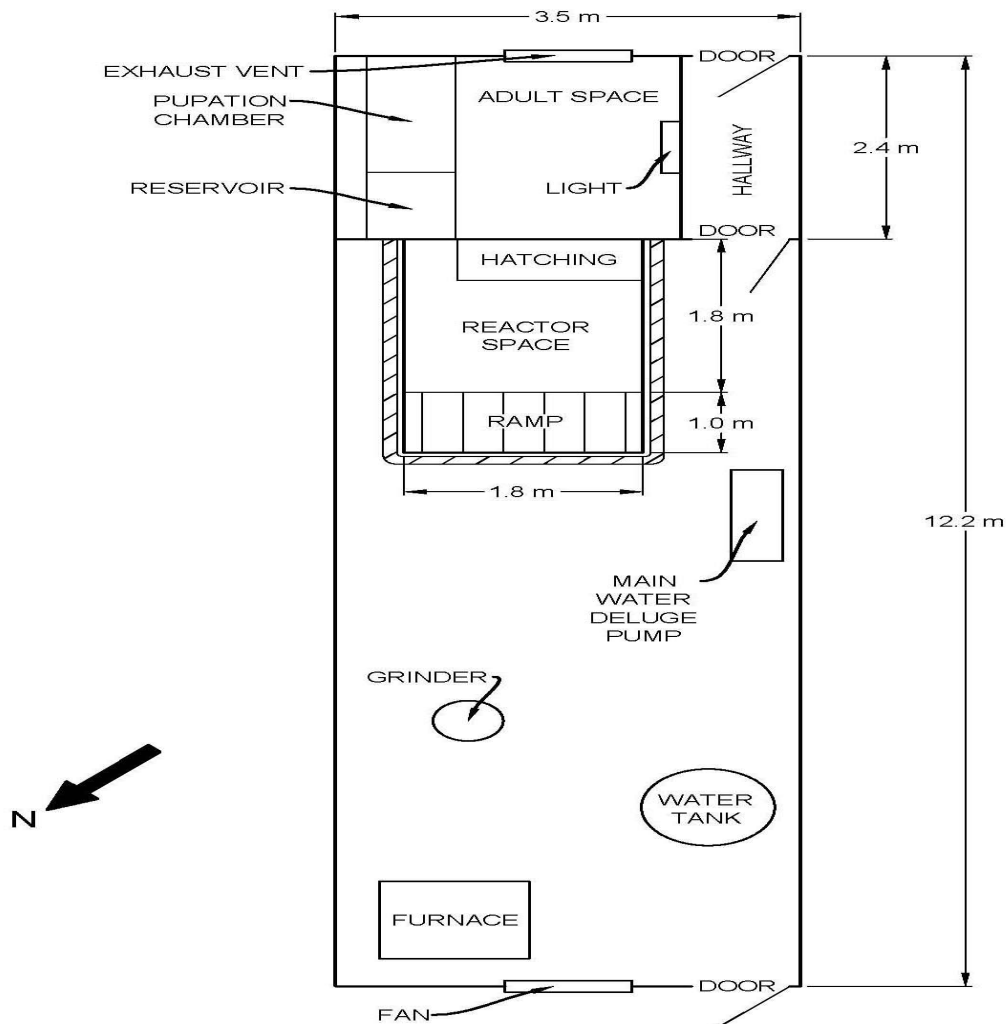


Figure 5 - Inner Greenhouse Layout

3.2.2 Subsystems

To organize study, the facility was divided into operational systems that facilitated a particular stage of the BSF's life cycle. These are:

- **The reactor space (RS)** occupied a volume of 1.0m^3 ($1.82\text{ m L} \times 1.82\text{ m W} \times 0.305\text{ m H}$) and was shaped like a rectangular prism. This subsystem was constructed on top of a wooden frame and made of $\frac{3}{4}$ inch plywood. It provided an area for the maggots to mature from freshly eclosed maggots to

their wandering stage. The area was lined with a waterproof membrane, BlueSkin™, which was attached according to the manufacturer's instructions. The RS was connected to the exit ramp and the hatchery. No physical border exists between the exit ramp and the RS. Window screening was used to separate the RS from the hatchery to contain the adults.

- **The exit ramp** was constructed of ¾ inch plywood and inclined at 40 degrees. It was also covered in the BlueSkin™ membrane to provide water resistance. The ramp provided an exit leading to the collection trough / pupation chamber where the migrating maggots pupated.
- **The collection trough** was rectangular in shape (1.82 m W x 0.914 m L x 0.457 m D), constructed of plywood and filled with wood chip (0.15 m deep) but was not lined. It was expected that the majority of the moisture from migrating maggots would be shed on the ramp and that any remaining moisture would be absorbed by the woodchip. It was at this location where the woodchip was sieved and the collected maggots were weighed and subsequently transported to the adult space.
- **The adult space** was a separate walled volume of approximately 14.5 m³, (2.5 m W x 2.35 m L x 2.46 m H). The adult space consisted of four walls with 2x4 construction covered with 0.15 mm (6 mil) plastic on both sides. In an attempt to discourage egg laying in undesired areas and escapees, all seams and joints were coated with acrylic caulking.

From an engineering perspective the behaviour and life stage requirements of the adults were more complex to cope with than at the larval stage. Adult requirements included providing drinking water, a volume of space to seek mates, exposure to light and a suitable location to deposit eggs. To address the water needs, a misting system was installed that sprayed onto window screens to provide drinking water in suitable particle sizes and add ambient humidity as

the water evaporated. To provide light requirements the room's walls and ceiling were made from translucent plastic. The majority of volume in the adult room was empty space to allow for aerial questing and mating behaviours. The entrance to the hatchery was located in the adult space.

- **The hatchery** was constructed of wood as a triangular prism (0.305 m L x 1.6 m W x 0.267 m H). The long side was covered by a sheet of plywood and the remaining surfaces were covered by window screening. Window screening was chosen because it would contain the adults in the adult room while allowing newly hatched larva to fall down into the RS. Eggs were laid on the screen directly.

3.2.3 Experimental Measurements - Methods

A number of parameters were measured and are described in the proceeding sections. Although the approach used in this research appears similar to those used in Diener et. al. (2009), this study is different because of the following reasons:

- This study was not an optimization study: the goal was not to establish optimal feeding rates but to determine the feeding rate under the conditions experienced by this research;
- The research was conducted on a larger scale than those conducted in Diener et. al. 2009. In this research there was only one replicate per cycle; and
- Maggots were never removed from the feed source during the resource consumption stage for measurements; they were allowed to migrate out on their own.

3.2.3.1 Reactor Space

In the RS, the temperature, number of maggots, weight of feed added, weight of waste remaining, moisture content (food and waste), area and depth of the food and maggot mixture were measured. The diet used in the study was discarded restaurant waste.

The diet was chosen based on experiments conducted by Nguyen (2010), which showed that restaurant waste was one of the diets that produced the largest maggots by mass. This diet was also available in the quantities required to sustain the expected number maggots generated by the facility. Detailed analysis about nutritional variability as it related to the diet choice and chemical analysis of the diet were considered outside the scope of this research.

The temperature in the reactor was measured by a data logger (HOBO Model # U12-012) every 40 minutes. The weight of the food was measured after it was mixed with water but prior to adding it to the RS using an electronic scale (Pelouze Model # 4040). Moisture samples were also collected at this point to determine the water content in the feed. Brief attempts were made to follow the feed application flux data (or feed loading rate) from Diener et. al. (2009) to determine the amount of waste given to the maggots. This approach was abandoned because the maggots could not be fed daily and the number of maggots per cm^2 could not be readily determined. Instead, the amount of waste required was estimated based on observed maggot numbers and previous observations of consumption.

The waste remaining after a completed cycle was measured after no visible maggots were apparent in the RS. In later cycles some of this waste was returned to the RS if small maggots were found to be present after a visual inspection. Separation of the freshly eclosed maggots from the waste proved impractical and the loss of these maggots would have negative effects on future cycles. Waste moisture samples were also collected at this point.

To prevent reactor fouling, waste was removed from all areas of the RS except directly underneath the connection to the hatchery as required. This done was because freshly eclosed maggots were most likely present at this location. In the remaining areas of the RS waste was simply scraped off the surface. Although this did result in some loss of older maggots, a fouled reactor would pose significant problems to the long term operability of the setup. The following calculations are available in Appendix C.

3.2.3.2 Moisture Content

In order to determine the moisture content of both the food and the waste, small samples of each were collected and weighed using a scale (Precisa Model # BJ100M) and set to dry for a minimum of 48 hours on top of a working heat source. The moisture content was then determined from the following equation:

$$(Eqn. 1) - \% \text{ Moisture Content} = \frac{\text{Wet Weight} - \text{Dry Weight}}{\text{Wet Weight}} * 100$$

Although the standard operating procedure involves the use of an oven, no such equipment was present at the research location. To verify the accuracy and consistency of this approach, twenty samples of feed waste were collected. Ten were dried in an oven and ten were dried using the above field approach. The results (see Appendix D) indicate a 4% difference in the average of the results. The oven dried samples consistently showed a higher content of water than their field method counterparts. To compensate for this difference, the waste reduction values were adjusted to 96% of their observed values.

3.2.3.3 Waste Consumption Rate

The rate of waste consumption is the important design parameter for future facility designs. Estimating this value required estimating the number of maggots and the quantity of food present in the reactor and the time it took for its consumption.

The sampling approach used involved collecting four 250 mL samples of the food and maggot mixture inside the reactor space. The number of maggots present in the samples was counted and then averaged across the four samples. Measurements of the depth (four readings) and area of the food and maggot mixture were also collected. The area was estimated to the nearest square or rectangle on the reactor space surface depending on the shape and size of the food pile. These values were used to estimate the number of maggots present in the RS according to the following equation (unit conversion factors are omitted).

(Eqn. 2)–

Total # of Maggots =

$$\frac{\text{Avg \# of maggots in samples} * \text{Measured Food Area} * \text{Avg Food Depth}}{\text{Sample Volume}}$$

This approach was developed because of the lack of literature available to guide these experimental conditions and to manage the amount of effort put into counting the maggots present in the RS. In order to establish consumption time the maggots were fed only when the food was completely consumed. This was established by visual observation: the food was considered consumed when it changed colour and texture. Another indicator that consumption was complete was when the maggots would start to wander away from the resource instead of remaining in it. The time between feedings was recorded and each feeding instance was termed a *feeding event*.

3.2.3.4 Daily Consumption Rate

Using the dry matter weights of the feed the daily consumption rate (DCR) was determined using the following equation:

$$(Eqn. 3) - DCR = \frac{\text{Waste Added}}{\text{Days Between Feedings}}$$

The rate of daily consumption on a per maggot basis (DCRM) was then calculated by the following equation:

$$(Eqn. 4) - DCRM = \frac{DCR}{\text{\# of Maggots}}$$

The DCRM was calculated for each feeding event. Because the number of times a feeding event occurred varied with each cycle, a cycle was considered complete when a wave of migrating maggots left the RS.

3.2.3.5 Dry Matter Waste Reduction

Using the total food weight given in the cycle and the weight of waste remaining at the end of the cycle, the amount of dry matter reduction (DMR) was calculated as a percent using the following equation:

(Eqn. 5)–

$$\% \text{ DMR} = \frac{\text{Total Dry Mass of Feed Given} - \text{Total Dry Waste Remaining}}{\text{Total Dry Mass of Feed Given}} * 100$$

The %DMR was then used to correct the DCRM to account for the amount of waste remaining in the RS after the completion of the cycle using the following equation:

$$(Eqn. 6) - cDCRM = \frac{DCRM * \% \text{ DMR}}{100}$$

The corrected DCRM values for each feeding instance were averaged to obtain one DCRM or average dry matter daily consumption rate for the entire feeding cycle on a per maggot basis. This was done to attenuate an artificial phenomenon that caused the cDCRM to increase towards the end of the cycle when normalized to a per maggot basis. This is discussed further in Section 3.7.

3.3 Exit Ramp and Pupation Trough

The exit ramp is where the maggots exit the RS during their wandering stage. The maggots were observed as they tried to traverse the ramp during migration waves. The number of maggots that successfully traversed the ramp and their chosen paths were observed. These observations would lead to future design improvements to the exit ramp.

In the pupation trough the captured maggots were screened out from the woodchips and the resulting maggots were counted and separated by colour into white (W) and

dark (B) groupings. The masses of each colour were then weighed and a total maggot output mass for each cycle was determined. The output mass was then used to calculate two values: 1.) the ratio of dark to white maggots and 2.) the productivity of the reactor space.

3.3.1 W/B Ratio & Maggot Mass Output

This ratio of dark to white maggots was meant to be an indicator of favourable conditions in the RS. Theoretically, the maggots should not leave the food source prior to acquiring sufficient nutrition for the remainder of their larval stage unless unfavourable conditions force them out. The acquisition of sufficient nutrition is conveniently marked by a change of colour from white to dark: if conditions in the feeding resource were adequate, the majority of maggots leaving the RS should be dark. The B:W ratio is obtained from the following equation:

$$(Eqn. 7) - W (White): B (Dark) Ratio = \frac{Mass\ of\ White\ Maggots}{Mass\ of\ Dark\ Maggots}$$

Theoretically, a ratio below one would indicate that the majority of maggots leaving the reactor are dark and have therefore successfully obtained their nutritional requirements and conditions in the reactor space throughout the feeding stage were satisfactory. Values greater than one should suggest the opposite because the conditions in the RS would be theoretically unfavourable. In reality the ratio would most likely need to be divided into ranges that indicate optimum, tolerable and problematic conditions.

The exit mass also measures the productivity of the RS. The exiting maggots are the value added product the facility produces but they are also required to perpetuate the colony. The estimate of the exit mass was used as a check to evaluate the number of maggots that successfully reached the pupation chamber from the reactor space.

Data collected by Nguyen (2010) for the nutrition resource used in these experiments showed that the average mass of one maggot over the entire cycle is 0.094 g. Using this value the number of maggots was estimated using a second approach that was

independent of the RS maggot number estimates. These data were used to calculate the percent difference of the two estimates from the following equation:

$$(Eqn. 8) - \% Difference = \frac{Reactor Est. - Pupation Chamber Est.}{Reactor Est.} * 100$$

This value could then be used to estimate the number of losses as a result of deaths or escapees between the RS and the pupation trough. If those losses are not considered significant the difference could be interpreted as an error in the reactor estimate of actual maggot numbers. The threshold of significance would depend on the harvest capacity of the system.

3.4 Adult Room and Hatchery

Estimating the number of adults present is necessary to evaluate the number of adults that successfully emerge from their pupal casing. Counting all of the adults present in the adult space is impractical because the adults are moving and double counting would inevitably result. Instead, the original approach used in the RS was modified for use in the adult room. Six 100 cm² areas (10 cm x 10 cm) were delineated in different locations where adults were observed to congregate. Adults present in these areas were counted and the six results were averaged. This was done with the same frequency as the RS measurements provided that adults were present. The corresponding areal density can then be used to estimate the total number of adults present given the total area of the adult space.

Another important variable is the number of mating pairs present. This was estimated by counting the observed mating pairs in the adult space. A qualitative assessment was also done to assess the activity of the adults in the given environmental conditions: high, medium or low. A high value indicates that the majority of adults were flying and mating, medium indicates an equal amount; and low values indicate that the majority of adults were stationary. It was reasoned that actively questing and mating adults found

the conditions abiotic conditions in the adult space acceptable. Higher numbers of active adults were assumed to indicate acceptable performance of the adult space.

Initially, the eggs laid during the continuous phase of operations were counted but this practice was eventually abandoned because of the risk of damaging the eggs. At this point in the research, the eggs were simply laid on the window screen separating the hatchery and the RS and handling them safely to weigh the mass was difficult and cumbersome. Adult space data can be viewed in Appendix E and hatchery data can be viewed in Appendix F.

3.5 Observations

The facility began operations on September 30th of 2009. The reactor space was seeded with one week old maggots that were mixed with chicken feed (the incubation nutrition source) and discarded fast food (the cycle's nutrition source). The initial mass of maggots could not be measured because separating them from the incubation food source was not practical. The reactor space was initially lined with a waterproofing membrane called BlueSkinTM. A misting system provided water to the RS and no drainage was provided in the RS in this system revision.

Twenty-four hours after the initial start-up it was observed that the BlueSkinTM did not contain the feeding maggots; they easily wiggled between any seams that were present and effectively destroyed the waterproofing membrane. The maggots were removed, the reactor space was cleaned and a continuous piece of pond liner was used to cover the exit ramp and the reactor bed. After the overhaul was completed (October 3rd 2009), the system was restarted. It became evident that the maggots liquefied the food waste during consumption and the reactor bed quickly became too wet causing the maggots to wander out.

This occurrence also revealed a design flaw: the sides of the RS were open and some of the maggots escaped the reactor bed via the side walls and spread throughout the greenhouse. A 2-inch ABS drain pipe was added to the reactor bed to allow excess

moisture to drain into a bucket that was periodically measured to determine the amount of waste liquids leaving the system; these volumes were found to be negligible, less than 1.5 liters per cycle (once added moisture to the feed source was reduced). The amount of wastewater increased in later cycles because the automated greenhouse cooling system and the reactor misters were the operated by the same pump: the demand for water was therefore base on cooling requirements. The situation was rectified when the systems were separated.

The containment issue remained a problem. When wet, the maggots will stick to almost any surface including plastic, wood and metals; these materials were easily traversed regardless of the inclination angle. The eventual solution to this problem was to direct migration and contain the maggots by fitting the entire open perimeter of the reactor with collection pipes on April 1, 2010.

During the first three months of operation there were two major flooding episodes caused by leaks in the greenhouse roofs during heavy rain events that drowned all the maggots and forced system restarts. Although some maggots were able to complete their life cycle, their numbers were significantly lower after the flooding.

During this three month period it was also observed that the digestibles could become anaerobic and that the RS required some form of aeration. To alleviate this issue a network of 12mm ($\frac{1}{2}$ inch) perforated CPVC piping was installed on November 25, 2009. The network was covered by 76.2 mm of pea gravel that was capped with a galvanized metal mesh (12mm x 12mm) so that it covered the entire surface area of the RS and 3.18 mm diameter holes were cut into the tubes to allow air to exit. A cross sectional view of this setup is shown in Figure 6. A five gallon air compressor provided air to the reactor bed fourteen times per day for one minute (fourteen operational cycles were the limit of the timer's capabilities).

Maggots preferred to feed in a position such that the head of the maggot is buried in the food waste and the spiracle is only slightly exposed. This feeding position is possible if the waste is viscous enough to prevent the maggots from sinking or tilting over. One

of the pea gravel's functions was to provide structural support for maggots so they could feed in this position. The gravel also served to disperse air flow from the supply piping and act as a filter that allowed liquefied waste to pass through it while retaining the solid waste in the active feeding location. All of the liquefied waste was captured and recycled through the system in using a trickling filter arrangement with recycled flow. Water was returned to the reactor vessel by hand.

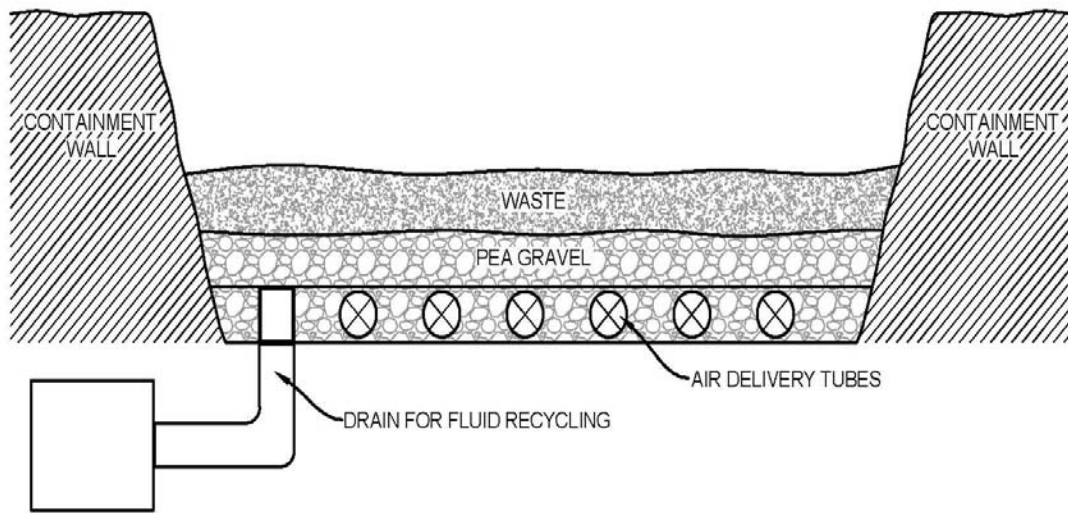


Figure 6 - Cross Sectional View of Trickling Filter Operation

The problems that caused frequent cycle restart conditions in the RS continued until the end of 2009 and thus, any data collected during this operational period was deemed unreliable and not used.

New larva became available in January of 2010. This operational period was considered the first cycle in which start-up problems were satisfactorily resolved and continuous operations began on January 13, 2010.

3.6 System Revision 1 – Results and Discussion

The setup constructed by the end of December 2009 provided satisfactory results and during later cycles, the highest number of maggots was eventually observed in the

reactor with the trickling filter approach. During their feeding the maggots liquefied the food, which then drained through the pea gravel and into a collection bucket and the contents of which were returned to the RS for further processing. The pea gravel also made it easier for the maggots to maintain their preferred feeding position, as shown in Figures 7A and 7B.

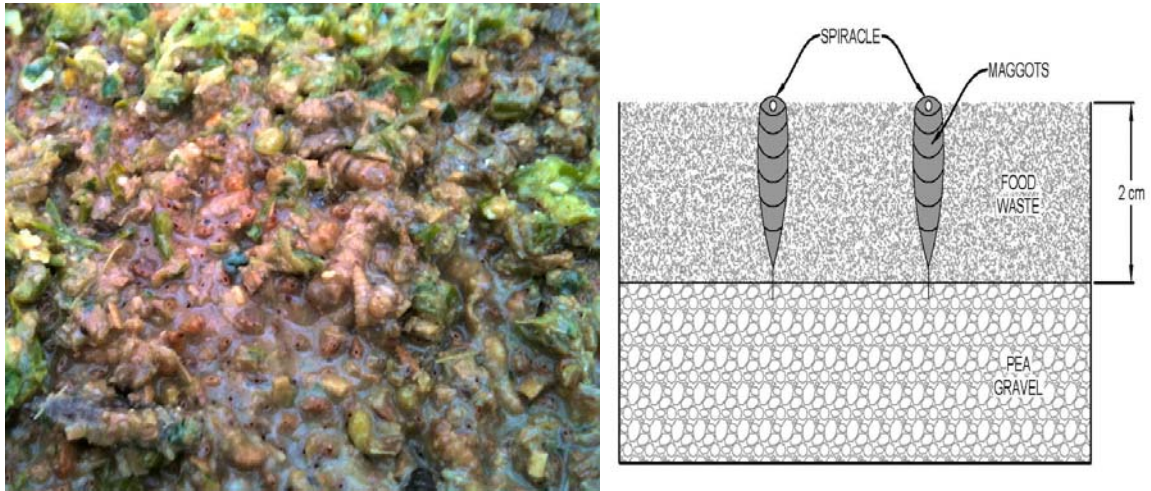


Figure 7 A & B - Preferential Feeding Position

3.6.1 Infrastructure Flaws

Draining the excess moisture proved troublesome in the initial stages of the research. The drainage pipe was located in the southeast corner of the reactor with the reactor floor sloped towards it. The window screening used to cap the drain prevented maggots from escaping but the small screen size would clog easily and required frequent cleaning to prevent excess fluid pooling. A satisfactory solution to this situation was never found but the problem was controlled indirectly by adjusting the quantity of the bulking agent used during the consumption period (in later cycles), regulating the misting system to supply less water when appropriate, adding less water to the feed and frequent cleaning of the drain cap.

The migration phase of cycles one and two demonstrated design problems with the exit ramp. The slope of the ramp proved too steep for its length and the majority of the maggots failed to climb it successfully. In fact, the majority of the maggots did not use

the main surface of the ramp. Instead, the maggots preferred to migrate along the edges of the ramp. This situation created bottlenecks because the maggots would form masses at the bottom of the ramp prior to exiting the RS via the ramp's edges. The sidewalls of the RS also provided an exit for the wandering maggots to climb up and over. Vertical walls were thought to be a sufficient deterrent against escape but this was not the case. An unknown number of maggots escaped the RS using this route and were thus not accounted in measurements of the RS performance. There were instances where, upon arrival to the research facility, large numbers of maggots were seen wandering on the floor of the inner and outer greenhouses.

3.6.2 Waste Consumption Results

Performance in the RS for the first two cycles was assessed in the reactor and adult spaces. In the reactor space the maximum number of maggots observed, the dry matter reduction and the average dry matter consumption rate were used to assess performance. The results suggested that the maggots were successfully consuming food, obtaining their nutritional requirements and reducing waste. The results for cycles one and two in the RS are summarized in Table 3.

Table 3 - Data Summary Cycles 1 & 2

Reactor Data											
Cycle	Start Date	End Date	Length (d)	Avg Temp (C)	Estimated Max Mag #	Std Dev	Dry Mass Given (kg)	Dry Mass Leftover (kg)	% Reduction	Avg Dry Consumption Rate (g/mag/d)	Std Dev
1	13/01/10	19/02/10	38	24.1	25937	6135	13.2	8.3	35.3	0.039	0.035
2	26/02/10	01/04/10	35	26.6	101209	11849	82.3	37.4	52.3	0.027	0.009

The feeding and migration stages lasted approximately the same length of time, or between 35 and 38 days. Temperature in the reactor was below the optimum range of 27°C to 33°C. Studies suggest that lower or higher temperatures affect the consumption rate of a resource by BSF larva. Waste reduction values between these feeding cycles were 20% different.

The possible reasons for the 20% difference in waste reduction are the significant differences between the two cycles in terms of the estimated maximum number of maggots and the consumption rate. The number of maggots was expected to increase in the second cycle from the first because of the lack of population limiting factors but the magnitude of this increase was unknown. The higher number of maggots present in cycle two is the reason that the per maggot waste consumption rate is lower. The reason for this phenomenon is explained in Section 3.7. The waste consumption rates for cycles one and two are shown in Figure 8.

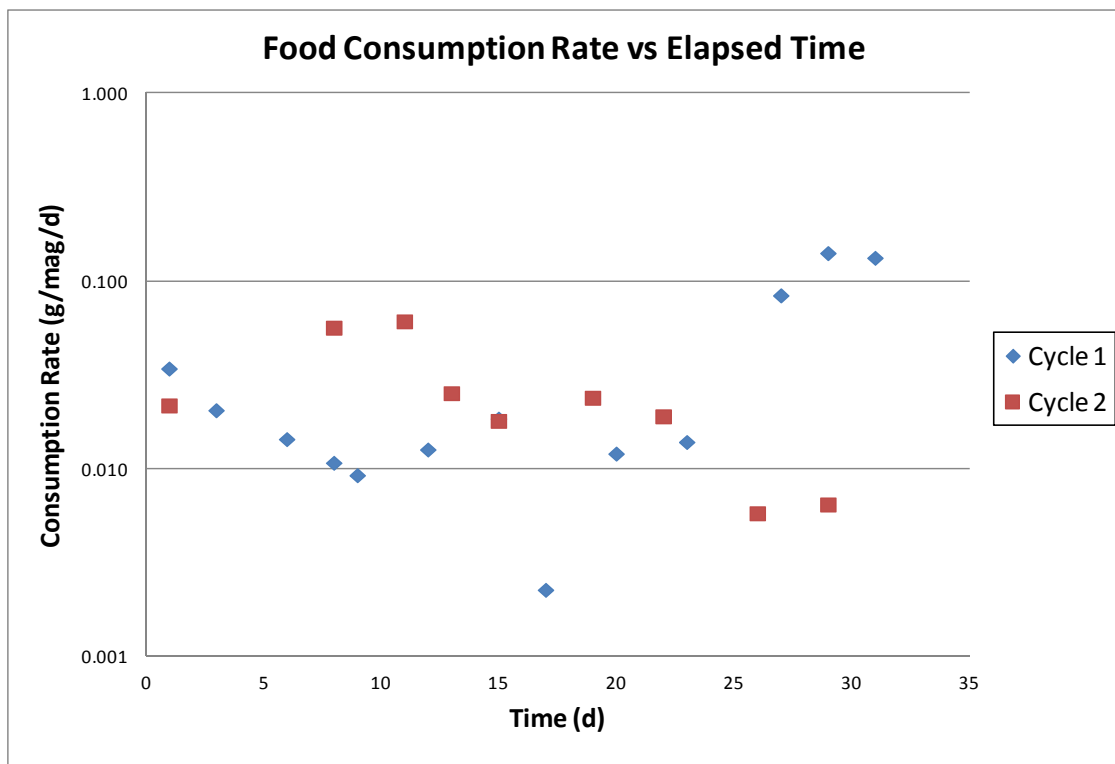


Figure 8 - Waste Consumption Rate Cycles 1 & 2.

Cycle one ended with no interruptions and an increase in the per maggot consumption rate is observed: the reason for this increase and its absence in cycle two will be explained in Section 3.7. Another interesting observation is the higher per maggot consumption rates for cycle one near day 23: this observation will also be explained in Section 3.7. Cycle two ended with a flooding event (caused by a rupture in a water supply line) that drowned a substantial portion of maggots but allowed some to complete their life cycle. Observations for cycle two ended on the day of the flooding

event. The exact numbers of drowned maggots were not counted or weighed because they were too numerous, and the maggots were water logged. Instead, efforts were focused on ensuring the survivors completed their life cycle to continue the colony for the next generation. The estimated number of maggots during the course of each cycle is shown in Figure 9. The increase in the number of maggots present was approximately five-fold. This suggests that many of the eggs laid by adults in cycle 1 survived to become maggots in cycle 2, demonstrating that the first version of the facility could successfully propagate the species. The observed increase in the maggot number does not necessarily mean that the actual number of maggots increased, but is likely instead a combination of the following:

- During sampling it is possible that very small larvae that were collected were not counted because they could not be seen;
- The maggots may have hidden in recesses of the reactor space and not become observable until their size increased; and
- In later cycles an influx of fresh hatchlings did cause an actual increase in the maggot numbers.

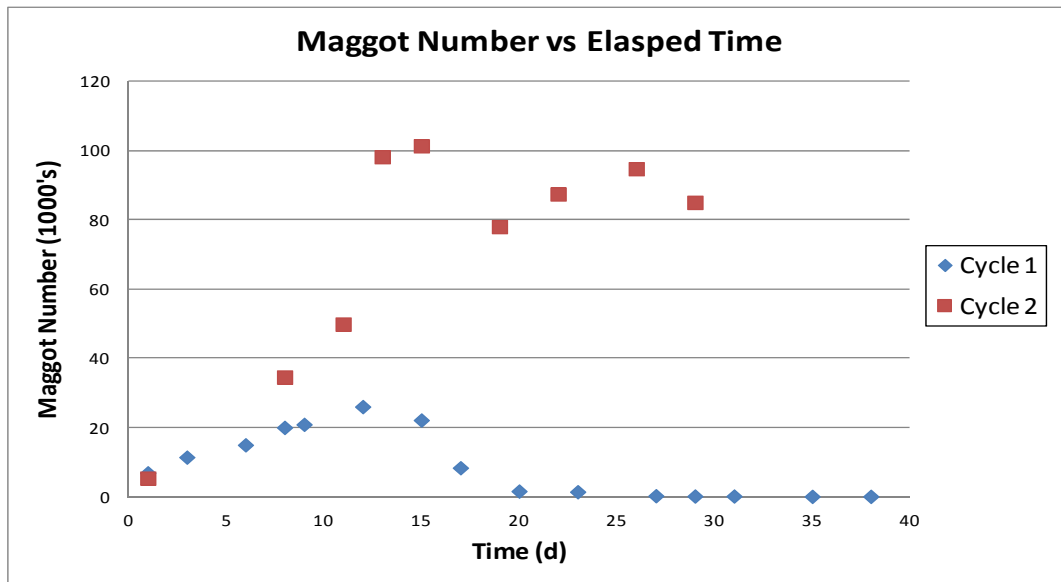


Figure 9 – Maggot Numbers and Cycle Length

3.6.3 Adult Space Performance

The habitat effectiveness of the adult space included measuring the amount of maggots that successfully completed the feeding stage and were captured in the pupation medium. These were considered inputs to the adult space and were sorted into white and dark maggots and their total weights were determined. The data are summarized in Table 4.

Table 4 – Adult Room and Hatchery Data

Adult Room & Hatchery Data															
Cycle	Avg. Temp (C)	Avg. Humidity (%)	Avg Light Levels (umol/m2/s)	Hatchery Avg. Temp	Hatchery Avg. Humidity	Total Mass of Mag Leaving (g)	Mag Exit Ratio (W:B)	Mag # Check	% Diff. from Reactor Est.	Egg Mass (g)	Est. Egg #	Est. Clutch #	# of Mating Adults	# of Adults Emerged	% of Mating Adults
1	NR	NR	NR	NR	NR	1743	2.27	11392	56.1	NR	NR	NR	NR	5696	NR
2	22.2	21.0	NR	NR	NR	4833	1.08	31588	68.8	NR	NR	NR	NR	15794	NR

The “Mag # Check” column (Table 4) was used to provide a check to the original reactor “Estimated Max Mag #” (see Table 3) using a percent difference calculation; a positive value indicates that the reactor method predicted a larger number of maggots present than those collected just before the pupation chamber. The maximum maggot number value from the reactor data was used as a basis for comparison. The difference of the reactor and adult space estimates calculated by this approach in cycles one and two is most likely the result of maggots escaping the collection trough and the flooding episode that prematurely ended the second cycle.

The difference in the maggot number estimates was also considered a rough indicator of the collection system’s performance and effectiveness of the system to contain and channel maggots to the pupation medium. The rationale is that the wandering maggots should stay in the pupation medium if the conditions are suitable for pupation and that lower maggot losses from escapes and deaths should result in a lower difference between the two estimates of maggot numbers. However because the two values are

simply estimates, this parameter was used as a guide only to evaluate the effectiveness of the collection system.

At this stage in the research assessment of adult performance was qualitative. Adults were assessed on their activity level. Active flying and mating was considered favourable to the health of the adults and by inference, a sign that the habitat was functioning adequately.

The introduction of the pea gravel in the RS also created an unforeseen issue when fully matured maggots began to pupate in it thereby eluding measurements. The previously mentioned reasons are the only situations, aside from human error, that could account for the difference in the maggot number estimation approaches. No evidence of pests, such as mice or raccoons, which would eat the BSF maggots, was evident at this stage.

The method proposed to estimate the number of adults present in the reactor space could not be implemented successfully. The uneven distribution of adults throughout the three dimensional volume of the adult space made the attempts impractical. The calculations outlined in the estimation approach relied on the assumption that the amount of empty space could be reliably measured but this was not the case. The amount of adults entering the system could be estimated via the amount of prepupa entering but the number successfully emerging and mating could not.

The approach was later modified to use the estimates obtained from the mass balance in Section 3.0.3 but this required the mass of the collected eggs. This later modification is the reason why only cycle eight from the continuous operational mode and cycles one to four from the batch mode have estimates of the adult number, mating pairs and emergence. An estimate of emergence, 50%, was obtained from data found in Holmes (2010) for an ambient relative humidity of 40%: these conditions were similar to those found in the setup for this research.

3.6.4 Adult Space Infrastructure Issues

Containing the adults proved troublesome. The adults can exploit any small opening as a means to escape. In particular, the acrylic caulking eventually failed and left open seams throughout the adult space. Adult flies would get trapped between the two plastic layers and eventually die. At its peak, the amount of open space appeared sufficient for aerial questing and mating. During one instance, over 75 mating pairs were counted, aerial questing was still occurring and many more mating pairs were evident. Perhaps the largest problem in the adult space was the dead adults. After mating the adults quickly die and their remains litter the floor. If not cleaned promptly, the dead fly bodies would attract small insect pests to the facility; although sealed to the greatest extent possible, the facility was neither sterile nor impervious.

Another issue was the amount of crevices present in the adult space. These were the result of imperfect mating surfaces created by the construction materials and they provided unintended egg laying sites for adults. Most of the eggs laid in these locations died and were typically not found until they had dried out. It is unclear why adults chose to lay their eggs in these locations when the hatchery was not visually saturated with eggs. The lack of aromatic cues from actively feeding maggots may have discouraged some adults from laying in the hatchery.

The adult chamber at this point in the research did not have artificial lights. Because the adults successfully produced eggs and seeking solutions to design problems in the RS were considered more urgent, selecting an artificial light source which could potentially encourage BSF adult activities was delayed until the next winter season.

3.7 System Revision 1 – Calculation Assumptions

The mass of feed consumed on a per day basis was calculated as a constant value throughout each feeding episode. For example, if 10 kg of food was given over ten days, the calculations would show that 1 kg of food was consumed per day by a varying

number of maggots. One of the notable drawbacks of this approach is that the rate of waste consumption on a per maggot basis appears to increase towards the end of the cycle. This is because maggots are leaving the RS but the calculated per day consumption for a feeding instance is held constant for a given feeding episode. Trying to account for all variables to develop a variable feed consumption rate proved too complex and was not feasible given the constraints of this research program. However, the error introduced by this effect was attenuated by using a cycle averaged cDCRM to calculate the waste loading rate for that cycle. These approaches were maintained throughout the remainder of the research.

It is unlikely that the DCR remains constant for several reasons.

1. The number of maggots present in the reactor is not constant with time. Maggots sometimes exit the food source and then return to it, while some maggots do not return at all and are permanently lost. It was not feasible to determine which maggots were feeding and which maggots were not.
2. Maggots die throughout the feeding cycle.
3. The mass of waste consumed per maggot changes with their size which is itself a function of time and the individual differences between maggots. In addition, maggot consumption rates also depend on the moisture content of the food and temperature both of which can also vary with time.

Measuring the combined effect that these variations have on the DCR was outside the scope of this research and the constant daily mass consumption assumption was considered a compromise between observational accuracy and the logistics of data collection. Unfortunately the actual number of maggots present in the RS could not be determined at the start of a continuous cycle because the freshly eclosed maggots would fall directly into the reactor bed and were not visible until they matured.

3.8 System Revision 2 –Subsystem Design Changes, April 4, 2010 to July 12, 2010

Based on the observations and lessons learned from the first two cycles the following subsystems were changed:

- Reactor space – a cover was added to help retain moisture over the RS and the number of mister nozzles was reduced from nine to six;
- Pupation trough – this was removed and a new pupation chamber was installed inside the adult space;
- Exit ramp – the inclination of the ramp was changed from 40 degrees to 34 degrees and fins were added;
- Water collection system – this idea was suggested by Glen Courtright of *Enviroflight*, Yellow Springs, Ohio;
- Adult space – a timer based watering system was installed so that the adults would have access to water twice per day;
- A maggot / water separator was installed immediately upstream of the pupation chamber;
- Sponges were added to the hatchery to provide a moist site for egg laying; and
- Misting nozzles were added to the inner greenhouse cooling fan to add humidity and cool the greenhouse through evaporation.

The design changes did not affect how variables were measured or calculated in the RS or the adult space. The most significant change in the second system revision was the collection of migrating maggots. Instead of directly migrating into the pupation trough, the maggots wandered into a system of 4-inch ABS plastic pipes. The pipes were cut along their axial length to create a channel. This channel was periodically filled with water that drained by gravity to the maggot / water separator. The function of the separator was to return water to the reservoir while allowing the migrating maggots to

continue on to the pupation chamber. The system's new operational flow can be viewed in Figure 10.

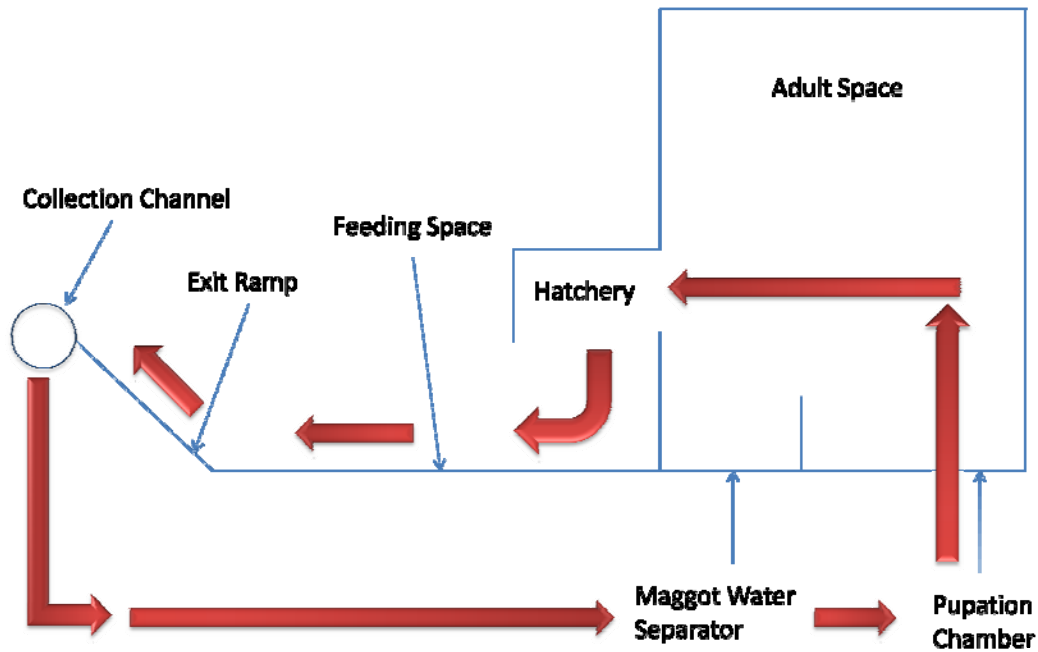


Figure 10 - BSF Movement in the System

The collection tubing was hung along the entire perimeter of the reactor space and the exit ramp so that maggot containment would no longer be an issue because they could be captured at all possible exit points. The exit ramp was still intended to be the main exit path and the ramp's slope was reduced during the installation of the collection system and fins were added to its entire surface.

The water collection system was powered by a 124 W (1/6 horsepower) submersible pump that delivered water at a flow rate of 98 L/min. This flow rate resulted in a water height of 1.0 cm in the collection tubes and because the flow rate of the pump was fixed, this height was not adjustable and remained constant throughout the research. The only possible adjustment was the on and off cycle times of the pump. The collection system is illustrated in Figure 11.

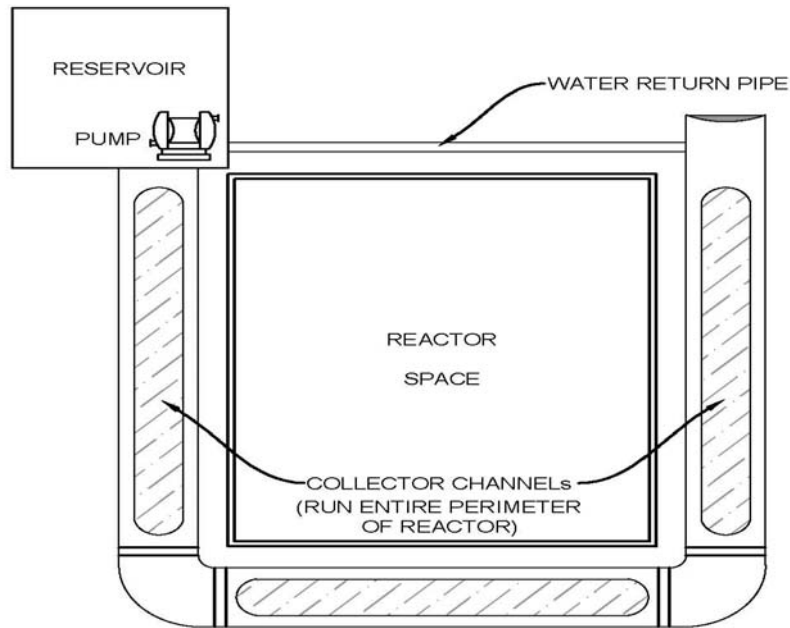


Figure 11 - Water Collection System

In addition to the collection tubes a method of separating the water from the maggots was necessary. The first version of this device consisted of a wooden frame with window screening on the top and bottom surfaces. The device was sloped downwards towards the pupation chamber. A five gallon bucket, the system reservoir, was placed underneath the bottom surface of the separator to catch water from the collection tubes. The device setup is shown in Figure 12.

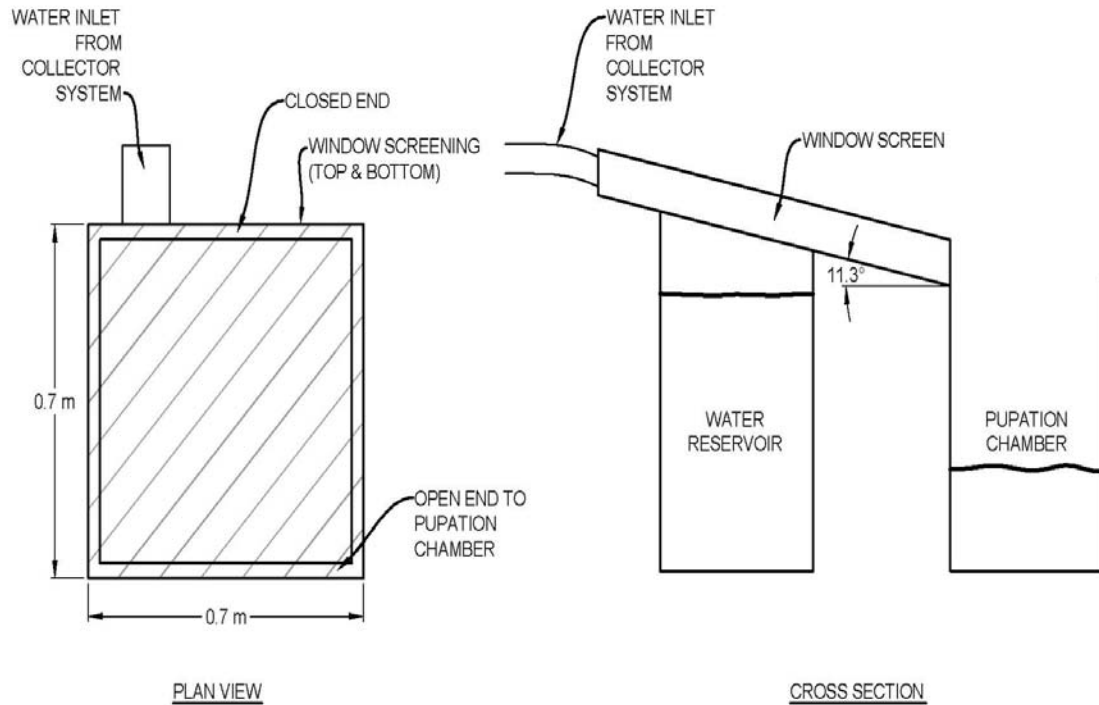


Figure 12 - Separator Revision 1

It was noticed in cycles one and two that the food in the RS needed additional moisture in excess of what the mister's timer settings were providing. It was hypothesized that the hot, dry air in the greenhouse was the cause. In order to stabilize humidity levels above the food source a plastic cover was added to the RS

Twelve dish sponges, measuring 10 cm L x 7 cm W x 2 cm H, were placed on top of the window screening. The sponges were two sided; one side with a filamentous plastic scrubbing edge and the other side was a soft pitted edge. The sponges were introduced because it was observed that some eggs from the first two cycles did not hatch because the egg clutches had dried out. Drying likely occurred for two reasons:

- 1.) The eggs were too exposed when they were laid on the screen; and
- 2.) The humidity in the hatchery was outside the tolerable range.

The crevices in the sponges were meant to protect the eggs clutches from desiccation and when wet, the sponges retained moisture in the hatchery. The sponges were kept moist manually.

The main 30-inch cooling fan for the greenhouse was fitted with six misting nozzles that were controlled by the timer in the hatchery and the adult space.

An experimental problem arose from the change in the collection method for the wandering maggots. The evaluation of the water separation device required that the maggots have the freedom to pass through the device so that its effectiveness could be assessed but if they traversed the device without being contained no reasonable estimate of maggot production could be obtained without resorting to sieving the wood chips in the pupation medium.

Sieving was a time consuming process and was considered inefficient. The solution was to contain the maggots in the separation device, collect the mass data, and then re-insert the maggots in the collection tube and observe if they successfully traversed the separation device. This was done every time maggots were present in the separation device. No other performance evaluation methods were changed from those outlined in revision one.

The system revisions were completed on April 1, 2010 and the system operated under these conditions for cycles three, four and five.

3.8.1 Observations and Discussion

Waste processing in the RS continued successfully and with the addition of the cover the food resource was kept moist throughout the cycles. Occasionally the food was found to be dry but such instances were reduced from being a consistent occurrence to once every two weeks. The performance markers were the same as in previous cycles, and the data are summarized in Table 5.

Table 5 - Reactor Space Summary Cycles 3, 4 & 5

Reactor Data											
Cycle	Start Date	End Date	Length (d)	Avg Temp (C)	Estimated Max Mag #	Std Dev	Dry Mass Given (kg)	Dry Mass Leftover (kg)	% Reduction	Avg Dry Consumption Rate (g/mag/d)	Std Dev
3	02/04/10	28/04/10	27	28.1	34749	6299	6.6	4.1	36.1	0.028	0.037
4	30/04/10	21/06/10	53	26.0	331236	40346	107.3	40.2	60.1	0.022	0.014
5	23/06/10	12/07/10	20	30.8	13314	7273	2.2	1.2	43.9	0.021	0.028

The outstanding cycle in this system revision is cycle four: its length, max maggot number, feed given and consumption rate all seem to be out of range when compared with the other two cycles. The long period in elapsed time could be the result of the lower than optimum temperature.

The observed increase in the number of maggots suggests that conditions in the adult room and hatchery during the third cycle were ideal for species propagation:

- A significant portion of larvae achieved their nutritional requirements;
- The collection system transported most of the wandering maggots to the pupation trough;
- Most of the pupae emerged as adults;
- Mating conditions were favourable; and
- Ambient conditions in the hatchery allowed a substantial number of eggs to mature and hatch.

The percentage of waste reduction in this series of cycles (3, 4 and 5) was higher than in the first two. This could be the result of better moisture management in the RS due to the cover and misting cycle adjustments. Improper moisture conditions have been shown to affect the efficient consumption of the resource (Fatchurochim et al. 1989).

3.8.2 Waste Consumption Rate and Maggot Numbers

The waste consumption rate for cycles three four and five are illustrated in the proceeding figure.

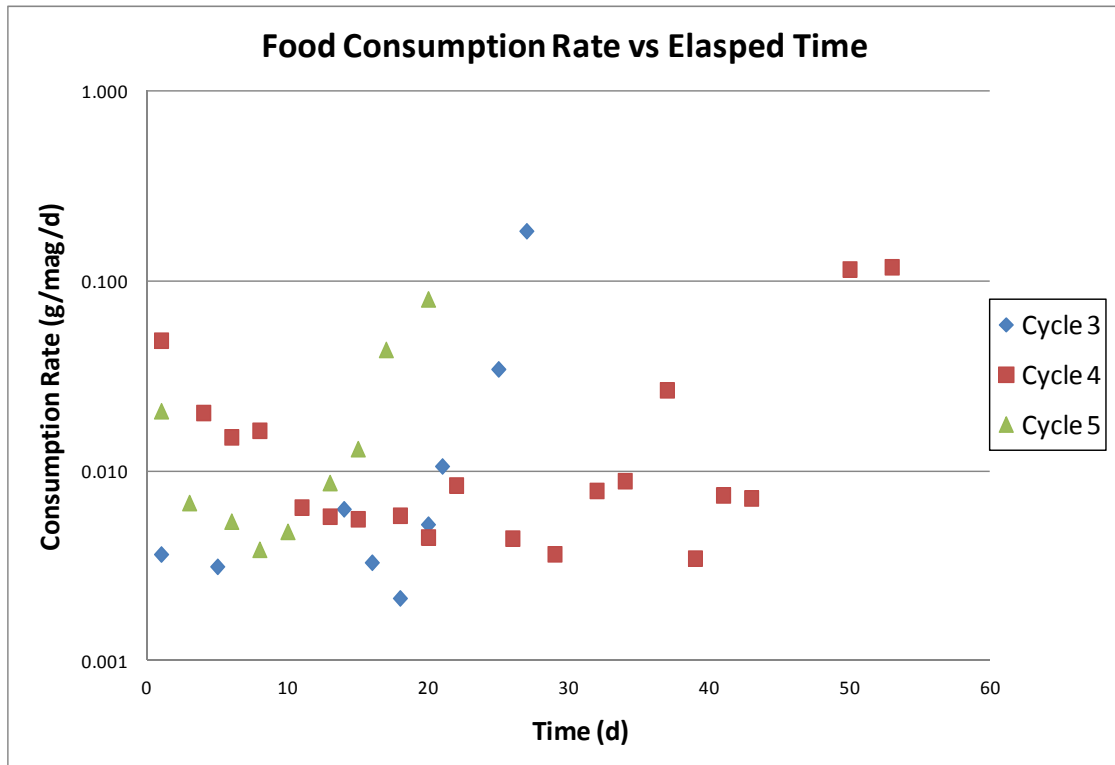


Figure 13 - Waste Consumption Rate

Cycles three and five appear to follow similar trends although cycle three's values are slightly lower; this was expected because of the larger number of maggots present in cycle three. Cycle four's pattern is different not just because of its length but in its trend as well. The rise in the consumption rate at approximately day thirty-six suggests that some deaths or outward migration occurred. This is immediately followed by a decrease suggesting that an influx of maggots occurred. It is possible that two cycles are present here or that smaller maggots were feeding in areas of the reactor that were not accessible to measurement, possibly in the pea gravel and they eventually migrated towards the surface.

The number of maggots present in the reactor during cycles three, four and five are shown in Figure 14.

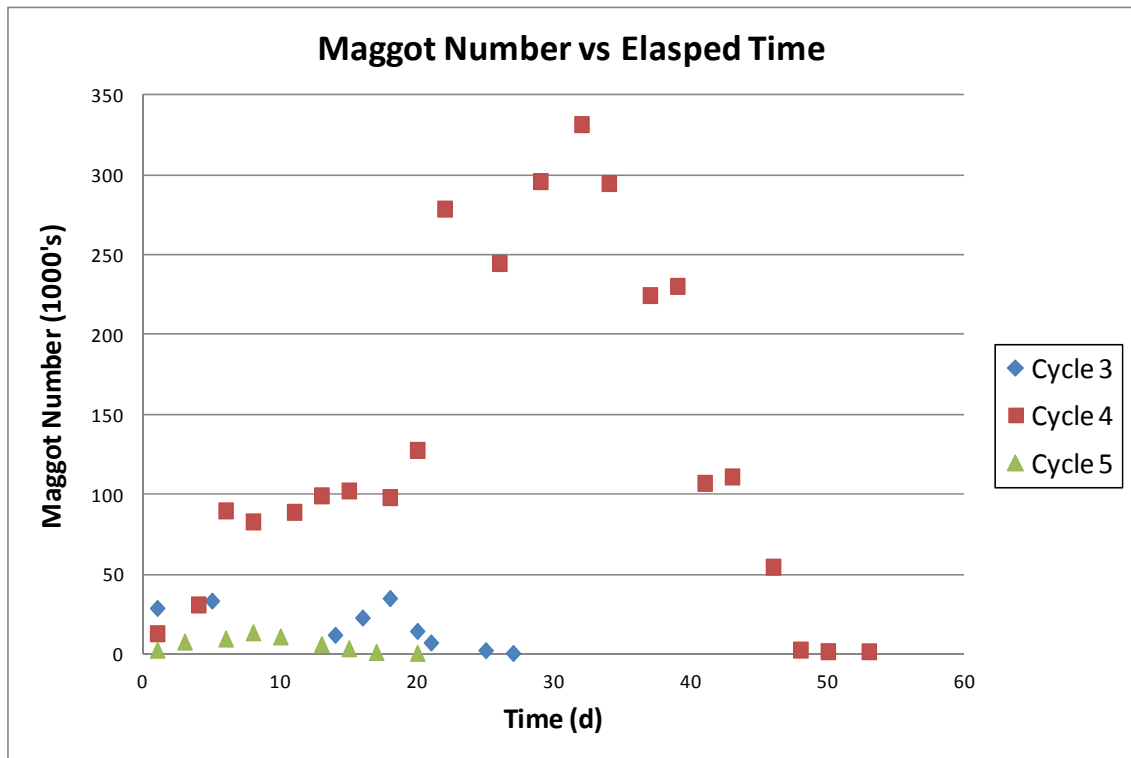


Figure 14 - Estimated Maggot Number

As previously stated the increase in maggot number between cycles three and four suggests the subsystems are functioning well. The increase in maggot numbers is nearly sevenfold.

Towards the end of cycle four a change in the maggots' behaviour was noticed. The maggots began to pupate inside the RS without migrating to the exit ramp. One possible reason for this is that the full area of the reactor space was not operational at the end of cycle four – there were parts of the reactor where no food processing was occurring. These void spaces were deemed suitable pupation locations by the wandering maggots. Adults from cycle four were observed to emerge from the RS.

Large numbers of adults were observed questing and mating outside of the adult space, in the main facility room, at the end of cycle four as a result of their pupation in the

reactor space. The majority of adults that were outside of the adult space escaped the greenhouse and presumably completed their life cycle elsewhere. The exact numbers of adults lost, and therefore potential eggs, were unknown. This loss of biomass significantly lowered the number of maggots observed in cycle five.

3.8.3 Reactor Space Design Issues

Another issue with the RS operation was the buildup of materials in the pea gravel at the end of cycle five. The void spaces (~ 3 to 7 mm) of the pea gravel were perhaps too small or conditions became too dry because they became clogged with semi-solid food. Eventually, the trapped food became anaerobic, and the maggots subsequently avoided it, and so the system was shut down. Cleaning the void spaces proved impractical so the gravel was removed during the second major set of system design changes and the trickling filter setup was abandoned. Some of the waste from cycle five was lost during the pea gravel removal process.

Although the trickling filter setup was abandoned because of clogging, it should be possible to solve the clogging issue with a change of media from pea gravel to a substance with a larger grain size and larger void spaces, such as using Styrofoam “peanuts” encased in a net. The Styrofoam peanuts would have the advantage of being low weight, inert, and could be contained as removable modular units simplifying the cleaning task. This approach was not implemented because of time constraints.

3.8.4 Exit Ramp Design Changes

During the middle of cycle three adjustments were made to the exit ramp, the slope was lowered and fins were added to the ramp. The lower slope proved easier for the maggots to traverse; the number of maggots that successfully negotiated the ramp on their first try was observed to increase. Fins were also installed on the exit ramp. The fins covered the entire inclined length of the ramp and were 3.8 cm wide and spaced 3.8 cm apart to create channels. Prior to their installation the only vertical edges that

existed were the ones made with the containment walls and these areas experienced the greatest maggot traffic. The traffic was so dense that clumps of maggots would be found at the base of the ramp resulting in a de-facto queue for maggots “waiting” to use the ramp. Conversations with entomological colleagues suggested that maggots prefer edges, probably as a guide, when moving to make their wandering more energy efficient. The addition of fins eliminated the bottlenecks and improved the usage of the ramp’s surface area by providing additional vertical edges. These before and after ramp configurations are illustrated in Figure 15.



Figure 15 - Exit Ramp Before and After Addition of Fins

Regardless of this fact, the maggots would exit the reactor space at the closest possibility to their feeding location; this is why the collection tubes were added to the two open containment walls of the reactor space. In future designs the exit ramp can be eliminated altogether and fins attached to the containment walls themselves simplifying system design.

3.8.5 Water Collection System

The idea to use water as a collection fluid was conceived by Glen Courtright of *Enviroflight*. The initial collection system in this research was a bin filled with wood chips. The maggots would exit the reactor space into the bin and would then be sifted, weighed and transported by hand to the adult space. The water collection system

greatly reduced the labour input into this task. It also eliminated the need for the maggots to exit at the ramp because the collection piping was installed along the entire open perimeter of the reactor space.

The collection system consisted of three parts:

1. The collection piping;
2. A reservoir;
3. The maggot and water separation device; and
4. The pump.

The pump was set to operate on a timer 14 times per day, roughly every 2 hours for 4 minutes. These settings were usually satisfactory when a full migration wave was not occurring. There were two instances when the collection tubes were found to be overflowing with migrating maggots because the pump was in between operational cycles. The temporary solution was to keep the pump operating constantly. This approach is inefficient because when the maggots are not migrating, the electricity to power the pump is wasted; the pump maintains water flow but there are too few, if any, maggots to collect. In later cycles this issue was resolved using a repeat cycle timer. In larger facilities the use of motion sensors to activate the pump would be a more effective solution.

The collection system also had an added benefit: the water used to transport the maggots through the collection system also cleaned them of residue. Interestingly residue accumulating in the collection pipes, the separation device and the water reservoir appears to be nutrient rich and encouraged algae growth. This collection water could be conceivably used for irrigation, particularly if the BSF facility is to be located near other agricultural operations.

In the previous system revision maggots exiting the RS would be covered in a film of liquefied food. This sticky film would cause the wood chip to stick to the maggots. It is unknown if this situation had detrimental effects on the pupae but residue began to

build up in the pupation chamber which necessitated removing the clumping wood chips.

The collection system was cleaned, using water, once or twice per run, depending on the number of migrating maggots. This helped maintain flow characteristics in the collection piping, efficient operation of the separation device and prevented damage to the pump by debris.

The reservoir of the system at this stage of the research was not modified. It housed a submersible pump that rested on top of a metal screen to prevent clogging of the intake manifold. The pump then returns water to the start of the collection piping via half pipe of CPVC.

3.8.6 Maggot / Water Separation Device

The performance of the separation device was poor; the setup separated the maggots from the water but there were some unacceptable drawbacks. The downward slope was not a favourable condition; the maggots were observed to prefer crawling upwards. This caused a situation where the maggots formed masses in the upper corners of the separation device; eventually the maggots destroyed the screening and were able to escape.

In addition, the downward slope allowed water to enter the pupation chamber because the window screening, which functioned as the separation material, allowed the water to form a film across it that in turn allowed incoming water to drain into the pupation chamber. The introduction of excess moisture created conditions that attracted other insects to the pupation chamber. Samples of the insects were collected and taken to the lab for identification; most were identified as benign so no initial efforts were made to remove them at the end of cycle three. Instead, efforts concentrated on preventing the water from entering the pupation chamber through the use of a baffle. While this approach helped, it was not considered a solution and the separation device was redesigned in the next system revision.

3.8.7 Pupation Chamber

By the end of cycle four, it was noticed that the number of adults emerging did not correspond with the amount of pupa collected. The pupation chamber was inspected and the inspection revealed that the majority of the water that entered the pupation chamber via the separation device did not evaporate as expected; instead, the water pooled at the bottom of the pupation trough and was absorbed by the wood chips. A substantial amount of pupa were presumed drowned and had to be discarded.

The community of insects present in the pupation chamber now included a worm species that was parasitic. It was observed that the worms attacked newly emerged adults by burrowing into their fat body; as many as three worms were observed feasting on one individual adult. No observations were made of worms attacking the pupae directly. In an attempt to save the remaining pupae and the colony, the wood chip was sifted to separate the pupae and the pupation medium was replaced with fresh wood chip. Despite these setbacks, sufficient numbers of adults emerged to propagate the colony for cycle 5.

3.8.8 Adult Space & Hatchery

The performance indicators from the adult room and hatchery are shown in Table 6.

Table 6 - Adult Space Summary Cycles 3, 4 & 5

Adult Room & Hatchery Data															
Cycle	Avg. Temp (C)	Avg. Humidity (%)	Avg Light Levels (umol/m2/s)	Hatchery Avg. Temp	Hatchery Avg. Humidity	Total Mass of Mag Leaving (g)	Mag Exit Ratio (W:B)	Mag # Check	% Diff. from Reactor Est.	Egg Mass (g)	Est. Egg #	Est. Clutch #	# of Mating Adults	# of Adults Emerged	% of Mating Adults
3	31.8	37.7	NR	NR	NR	1712	0.90	11190	67.8	NR	NR	NR	NR	5595	NR
4	31.9	31.5	NR	NR	NR	9817	2.05	64163	80.6	NR	NR	NR	NR	32082	NR
5	35.6	26.3	NR	NR	NR	1245	2.27	13314	38.9	NR	NR	NR	NR	6657	NR

The differences between the maggot numbers observed in the adult space and those estimated in the RS were explained in Section 3.8.2.

Light levels were not yet measured but because mating and egg laying were occurring successfully, light conditions were not investigated immediately. Despite adjustments made to the misting system's timer to correct humidity levels, the ambient humidity was outside the optimum range. When coupled with high temperatures, these circumstances were thought to be responsible for the desiccation of an unknown number of eggs.

A snap shot of the temperature and humidity levels for the periods in question are illustrated in Figures 16 and 17. From these figures it can be seen that optimal ranges were difficult to maintain.

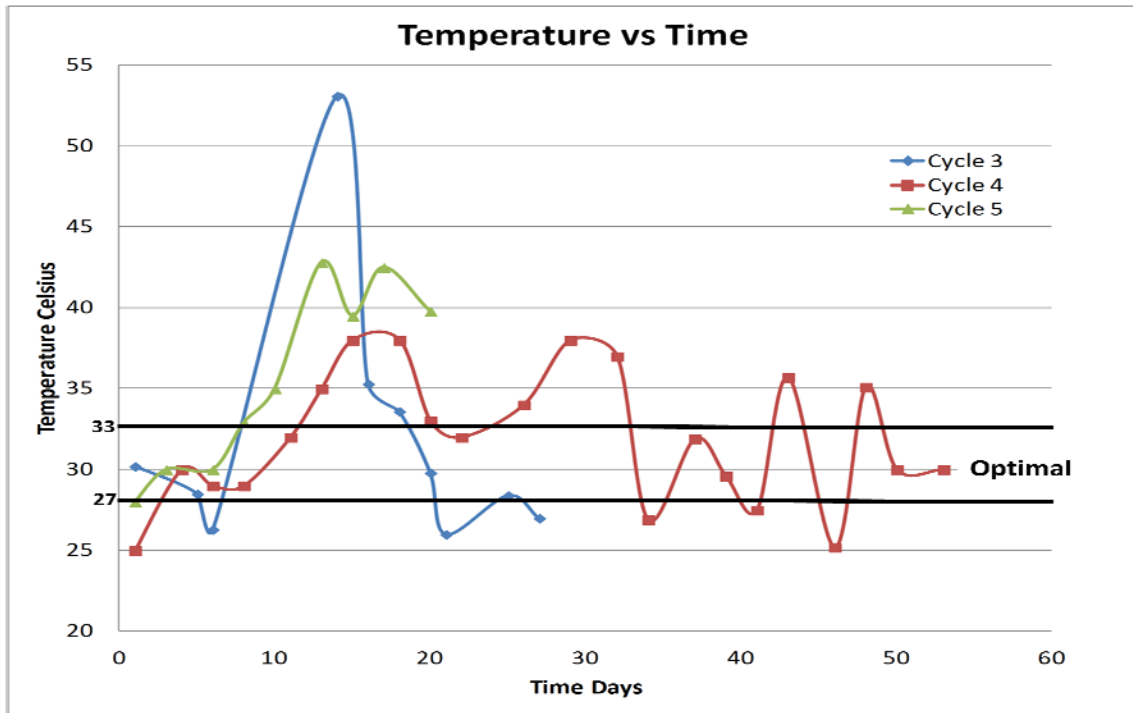


Figure 16 - Adult Room Temperatures, Cycles 3, 4 & 5

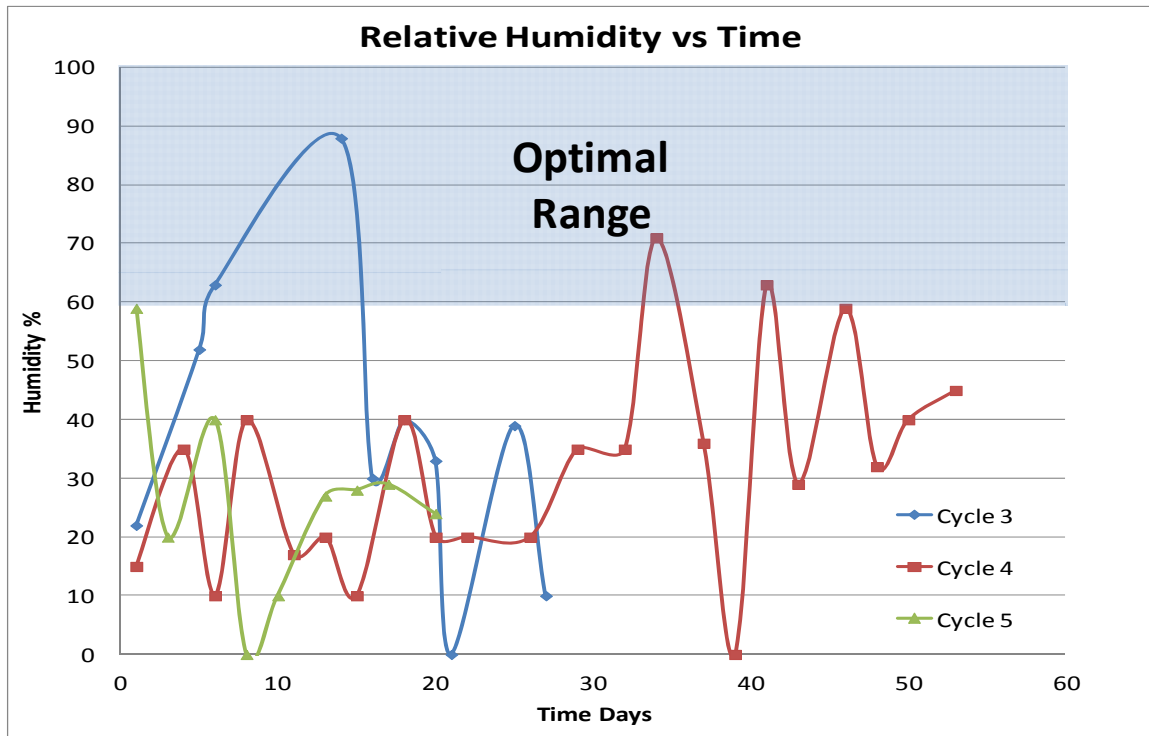


Figure 17 - Adult Room Relative Humidity, Cycles 3, 4 & 5

In an attempt to prevent egg desiccation, two misters were removed from the adult space and relocated to the hatchery. Manual watering had proved insufficient to maintain adequate moisture levels. The addition of the two misting nozzles improved ambient humidity levels but the nozzles' operation was not independent of the adult space and RS misting timer settings. After operating, the misters typically leak because of residual pressure in the feed lines. Although this was not a problem in the RS or the adult space, it was a problem in the hatchery because egg clutches near the misters were inadvertently drowned. The sponges underneath the misters were removed to prevent further egg losses but the hatchery demands for moisture were different than that of the RS or the adult space. Based on these experiences, independent controls for the water delivery systems are recommended for each subsystem where water is required. This situation could not be resolved until the next system revision.

Adult females were also observed laying eggs in the hatchery but in locations that were unsuitable for egg survival such as the crevices on the plywood, the edges of the window screening and imperfections at corners and seams. These construction flaws allowed the adult females to access unfavourable egg laying sites. This is illustrated in Figure 18.

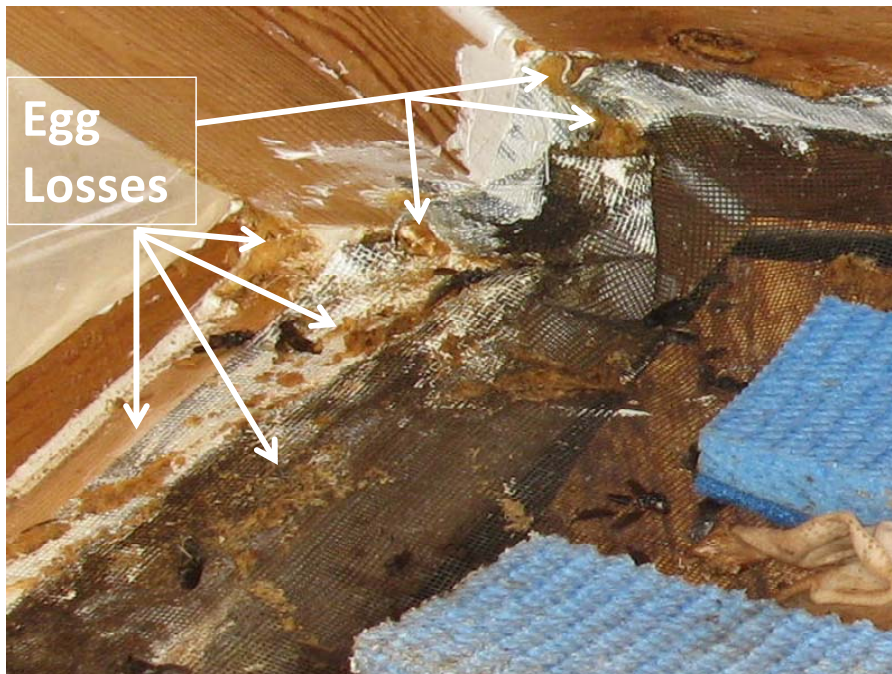


Figure 18 - Unfavourable Egg Laying Sites in Hatchery

Many egg clutches appeared desiccated, most likely because of their location in the hatchery. Hatchlings from these eggs were unable to reach the RS and consume the nutrition source. These losses were considered avoidable and therefore the hatchery was redesigned in the next system revision. Further losses were observed with the freshly emerged hatchlings. The scrubbing face of the sponges consisted of a plastic mesh that allowed the hatchlings to become trapped and eventually drown. The number of hatchlings lost in this fashion could not be determined. A temporary solution was to remove the scrubbing edge from the sponges. This approach was met with limited success because the hatchlings would burrow into the sponge itself and become trapped. This situation was not repaired until the next system revision so the system operated with these losses.

3.8.9 Seasonal Issues

Summertime operation presented new issues. During the winter months exchange with the outside air was limited and as a result, maintaining environmental conditions was not overly problematic. In the summertime the double greenhouse effect caused

temperatures to reach intolerable levels without active cooling. The greenhouse relied on a constant flow of outside air, coupled with evaporative cooling, to maintain tolerable temperatures. This constant influx of external air made internal humidity levels the same as external levels: when external humidity levels were adequate the circumstances were not detrimental but when they were inadequate, there was little that could be done to stabilize humidity to optimum levels.

3.9 System Revision 3 – Subsystem Design Changes, August 23, 2010 to January 31, 2011

After completion of cycle five the system was shutdown, eggs were collected and incubated at the University's Biology lab and the following second set of major revisions were implemented:

- The trickling filter setup was abandoned and the use of a potentially digestible bulking agent was introduced;
- The air compressor and its associated piping were removed;
- A new cover was constructed for the exit ramp to deflect air from the greenhouse cooling fan away from the RS and the cover over the RS was replaced;
- A separate misting system for the RS was installed and the number of nozzles was reduced from six to five. The adult space and hatchery misters were still controlled by the same timer;
- The water maggot separator was removed and redesigned;
- The collection system's reservoir was replaced with another container of larger volume;
- The hatchery was torn down and completely redesigned to remove unwanted egg laying sites;
- New plastic egg cartridges were introduced;
- Separate temperature and humidity sensors were installed in the hatchery;

- Light levels were measured in the adult space and outside; and
- Lights were installed in the adult space.

The removal of the trickling filter setup eliminated problems with clogging but because the maggots used the gravel's void spaces for support, the use of a bulking agent became necessary. Straw was chosen for this task because it was abundant, inexpensive and potentially digestible by the maggots. Even if the maggots did not digest the straw, its presence in the finished residue was not expected to affect its usability in agricultural applications. The straw was purchased from local suppliers and was ground up prior to use in the grinder to reduce its size.

The waste was ground to the consistency of oatmeal for storage. This was controlled by the careful addition of water during the grinding process. Exact records of the required quantity of water to achieve this grind were not kept. The baled straw was too long for direct addition into the feed. The straw was ground so that the individual stalks measured approximately 1 to 3 cm in length.

Aeration was replaced by hand turning of the waste to provide oxygen. This was not done on a scheduled basis but only when odours became a problem. Odours were generally not an issue because the maggots would consume the waste before odours became a significant problem.

However during the course of the experiments foul odours were observed four times. The generation of odours originates with anaerobic bacteria. The maggots and the bacteria are thought to be in direct competition with each other for the waste food. In three of the cases the odours were observed during the initial startup period between September 2009 and December 2009. In all three cases the odours were present on a Monday after a weekend. The last case of odours occurred on Monday October 18, 2010 during cycle 7. The site was visited every other day unless holidays, bad weather or site access issues prevented it. This suggests that the time before odours become a

problem is in the range of 2 to 3 days without any aeration for the feed used in this research.

The old reactor space cover was replaced because of damage it sustained during the previous cycles and to accommodate the water collection system. The old cover would sometimes fall into the collection piping clogging the system and causing spillage of the collection fluid. The separate misting controls for the RS and adult room and hatchery allowed for more efficient use of the water: the water supply demands could now be met separately for each subsystem.

The most extensive design changes were implemented on the hatchery. No part of the old hatchery was saved. The shape of the hatchery was changed from triangular to rectangular. The walls of the new hatchery were constructed from high density polyethylene instead of plywood. The smooth surfaces were meant to discourage egg laying in unwanted locations. Any imperfections or joints were sealed with acrylic caulking.

The hatchery was also divided into two separate areas each measuring 0.762 m L x 0.305 m D. These areas were the openings that separated the hatchery from the RS that was located below. It is into these openings that the egg laying cartridges were placed. The cartridges were made of plastic cardboard from advertising signs. The plastic was cut into 0.305 m L x 0.003 m W x 0.0254 m D pieces to expose their inner channeled edge. Each cartridge had two holes drilled into their smooth side so that two threaded steel rods could be inserted to join all the cartridges together. The channel openings measured 5 mm L x 3 mm W. After both egg laying units were assembled, they were installed in the hatchery and the setup was checked to ensure that no openings existed that could allow adults to escape. The two misting nozzles were reinstalled to provide moisture. The comparatively hard surface of the plastic was expected to prevent hatchlings from becoming entangled or trapped in the hatchery infrastructure.

Independent temperature and humidity readings were now measured via a newly installed sensor in the hatchery. The completed egg laying assembly and the hatchery are illustrated in Figures 19A and 19B.



Figure 19 A & B - Hatchery Second Revision

The separation device was also completely redesigned. Instead of a sloped channel a rectangular cube was constructed and lined with window screening and perforated sheet metal. The horizontal position was intended to eliminate water from entering the pupation medium. Figures 20A and 20B illustrate the separation device.



Figure 20 A & B - Separator Second Revision

The window screen was inclined slightly upwards towards the pupation chamber to encourage migration in that direction. The exit was rectangular in shape to facilitate the use of a cover to prevent escape for measurement purposes. All joints and seams were sealed with acrylic caulking to prevent escapes and ensure water tightness.

The literature suggested that insect vision is tuned to the UV-A, blue and green regions of the electromagnetic spectrum (~315 to 620 nm). The adult space housed two lighting systems. The first was a 1 kW Sunmaster™ warm deluxe metal halide bulb contained inside a ventilated reflector. A ventilated reflector was used to prevent flies from contacting the bulb during operation. The second lighting system consisted of two 40W UV-A spectrum fluorescent bulbs (Sylvania 24922 F40/350BL). These lights were meant to supplement sunlight in the winter months and were initially operated together by a timer to provide 12 hours of daylight from 6 AM to 6 PM. Light intensity readings were measured by a quantum photon flux meter (Spectrum Technologies Model #3415FSE) (400 to 700 nm) at approximately a 1.5 meter height between 10 and 11 AM. Five individual readings were taken inside the adult space and one reading was collected outside.

Cycle six began on August 23, 2010 when incubated maggots from the University were seeded in the newly revised system.

3.9.1 Observations– Subsystem Infrastructure

Waste processing continued without significant operational problems except for a minor flooding event caused by a clogged drain and excessive watering from the misting system. This situation was resolved by adjusting the misting system's timer to provide less water. Maggots were observed to consume waste in their preferred feeding position.

During the summertime months the programmed operational cycles provided by the timer were inadequate for cooling and watering demands. The use of a repeat cycle timer was introduced for the misting pump. Every thirty minutes the system would operate for two minutes.

The water collection system was also changed to operate on a repeat cycle timer. After installing the timer the collection tubes were not seen filled with maggots, instead the maggots were seen trapped in the separator.

The second revision of the separator prevented the entry of water into the pupation chamber but it was observed that the maggots preferred to stay in the separator and not exit the into the pupation chamber. Furthermore, the separator was difficult to clean and it soon became overgrown with algae. The separation device was redesigned to its current form and installed on October 29, 2010. The final revision used a section of ABS covered in window screening with an opening (0.305 m L x 0.102 m W) cut axially. The entire tube was then wrapped with a metal screen consisting of circular holes with alternating diameters of 3 mm and 1 mm. The setup is illustrated in Figure 21.

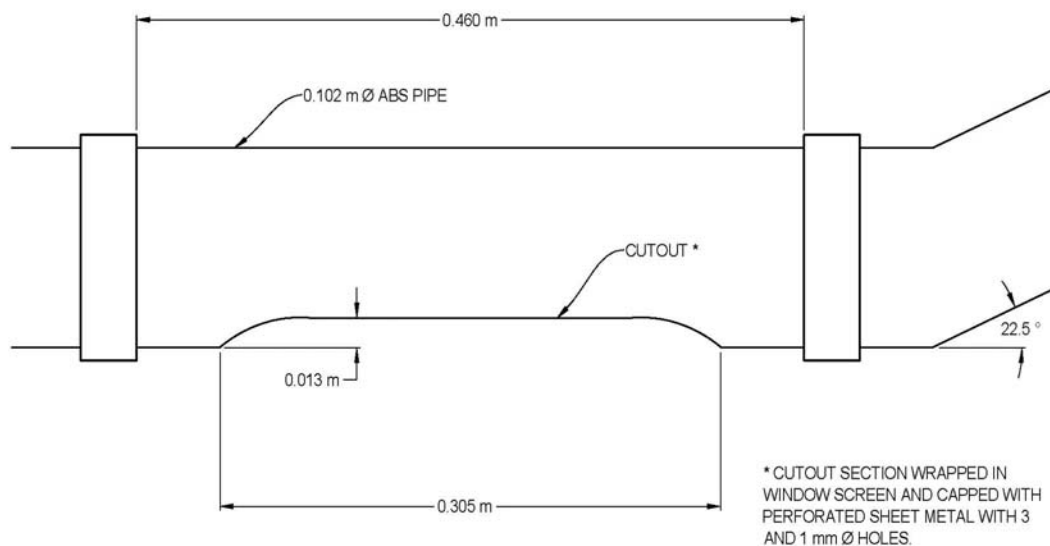


Figure 21 - Separator Final Revision

This version of the separator has proven the most effective at separating water from the maggots and channeling maggots to the pupation chamber with minimal moisture.

Periodic cleaning of the window screen and mesh are still required but this occurs once or twice per run. This current revision also facilitates estimating the number of maggots because the smaller opening is much easier to block.

3.9.2 Results and Discussion

The system performance indicators are shown in Table 7.

Table 7 - Data Summary Reactor Space Cycles 6, 7 & 8

Reactor Data											
Cycle	Start Date	End Date	Length (d)	Avg Temp (C)	Estimated Max Mag #	Std Dev	Dry Mass Given (kg)	Dry Mass Leftover (kg)	% Reduction	Avg Dry Consumption Rate (g/mag/d)	Std Dev
6	23/08/10	20/09/10	29	22.0	10680	5955	5.5	3.3	37.8	0.029	0.011
7	22/09/10	19/11/10	59	20.6	111544	21578	50.4	18.7	60.3	0.015	0.008
8	22/11/10	31/01/11	71	20.0	184230	85262	23.3	10.9	51.0	0.008	0.008

The average temperatures in cycles six, seven and eight were low compared to those in other cycles but the mass of organic waste reduction appeared unaffected and comparable to that observed in cycles with higher average temperatures. Cycles 7 and 8 lasted longer than expected. The estimated number of maggots in the system continued to grow until the system was shutdown suggesting that conditions in the system were at least satisfactory for species propagation. The average consumption rate for each cycle also appeared to be low in cycles seven and eight but this is consistent with increased maggot numbers. Pupation inside the RS was nearly eliminated with the removal of the trickling filter setup but the occasional pupae were found in the dried waste. Adults were not found in the main operations room of the greenhouse: any pupae found in the RS were assumed to be dead.

The waste consumption rates for cycles six, seven and eight are illustrated Figure 22.

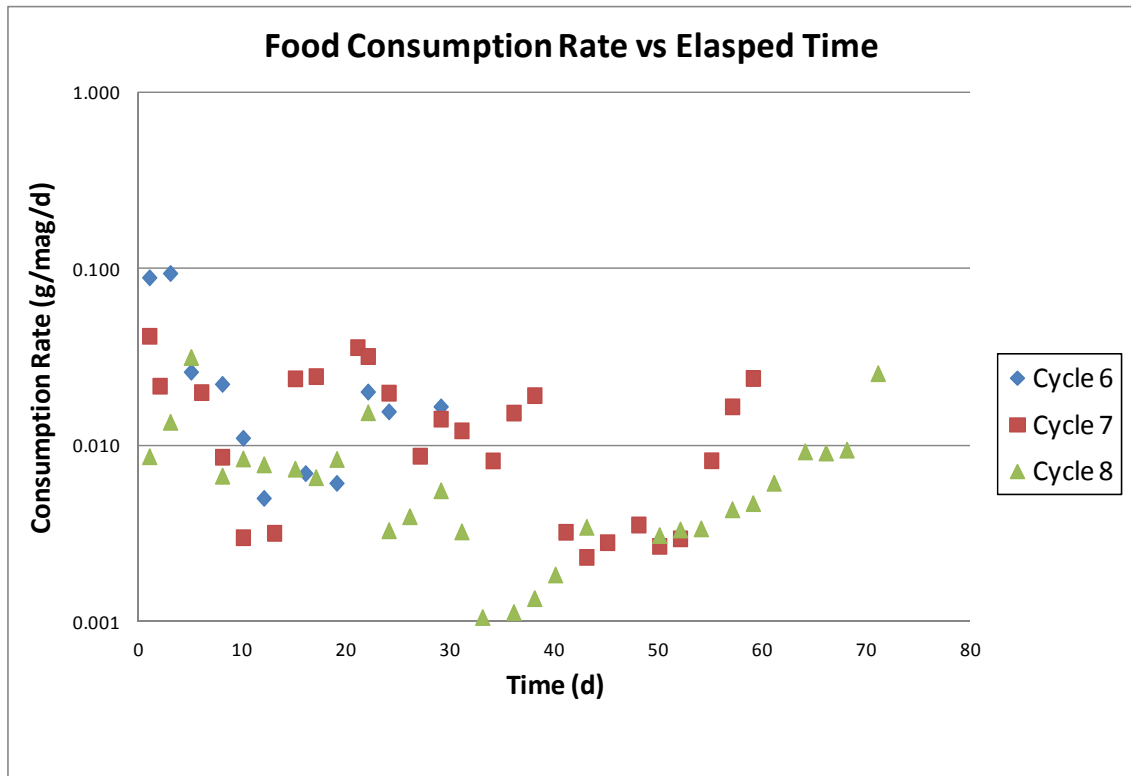


Figure 22 - Waste Consumption Rate

Although the average waste consumption rate for cycles seven and eight differ, the trends for both appear similar. Cycle six follows a similar shape but because the overall number of maggots is less, its values are somewhat larger. Cycle six is about half the length of cycles 7 and 8. The number of maggots present in the reactor for cycles six, seven and eight are shown in the Figure 23.

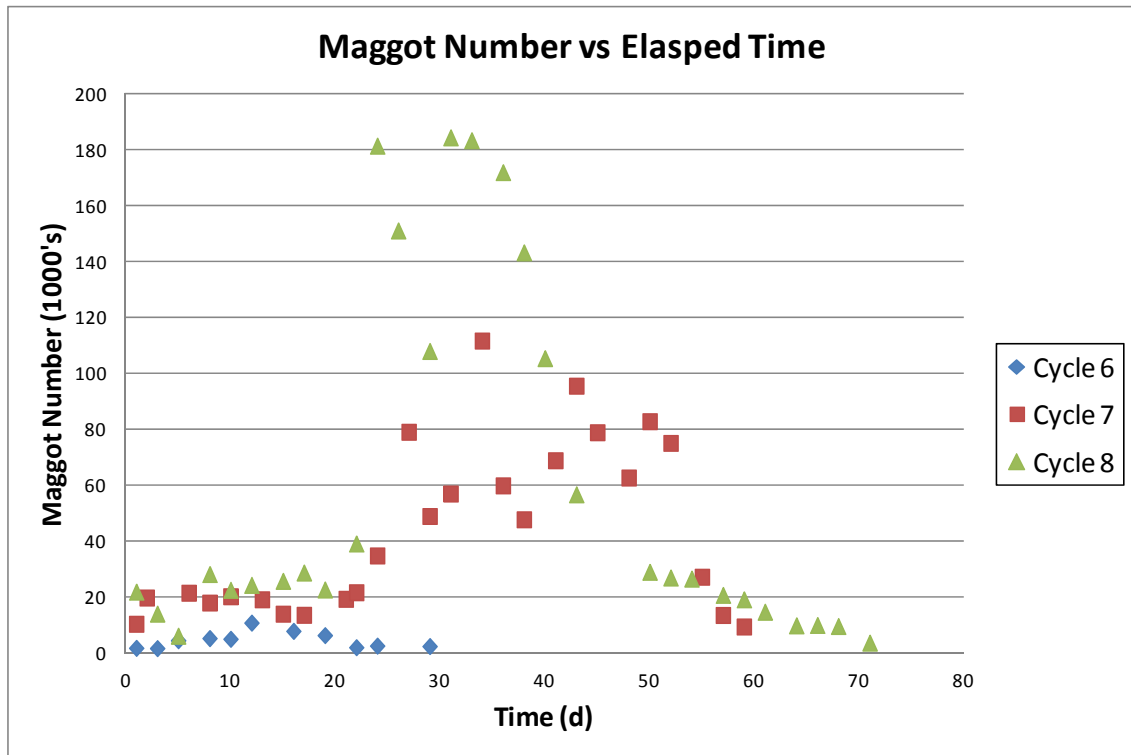


Figure 23 - Estimated Maggot Numbers

3.9.2.1 Adult Space

There were no problems with operating the collection system or its timer settings; no maggots were seen on the floor suggesting the timer settings that controlled the collection system's operation were satisfactory.

The redesign of the water / maggot separator performed well; maggots easily traversed the device, no water entered the pupation chamber, the maggots were washed clean of any debris and maintenance was simplified. This design has not been changed and has been carried forward to the final version of the system.

The performance metrics for the adult space are listed in Table 8. The NR stands for no reading. The mass of the eggs were not measured at this stage of the research because of the system's operation in the continuous mode as described in Section 3.1.2.1. Eggs are also very fragile and handling them was avoided whenever possible to minimize lost maggots to future cycles.

Table 8 - Adult Space Data Summary Cycles 6, 7 & 8.

Cycle	Avg. Temp (C)	Avg. Humidity (%)	Avg Light Levels ($\mu\text{mol}/\text{m}^2/\text{s}$)	Hatchery Avg. Temp	Hatchery Avg. Humidity	Total Mass of Mag Leaving (g)	Mag Exit Ratio (W:B)	Mag # Check	% Diff. from Reactor Est.	Egg Mass (g)	Est. Egg #	Est. Clutch #	# of Mating Adults	# of Adults Emerged	% of Mating Adults
6	31.2	42.9	195	27.3	34.1	796	2.47	5203	51.3	NR	NR	NR	NR	2601	NR
7	29.3	39.7	202	27.0	32.1	6445	4.56	42124	62.2	NR	NR	NR	NR	21062	NR
8	28.1	30.8	208	27.0	26.1	7391	3.99	48307	73.8	14.706	749036	1888	3776	24154	16

Average temperatures in the adult space and the hatchery are both within the optimum range. Average humidity however was well below the 60% mark.

Maggots migrating out of the reactor were trapped with no observable losses.

However, the difference in maggot number estimates between the reactor and those from the separation device was notable. It was not until the facility was dismantled at the end of the research that a tear was located in the liner. When the liner was removed, a large number of maggots, some still migrating, were found underneath. The numbers of maggots that were lost in this fashion and the time when the tear occurred were unknown.

3.9.2.2 Lighting System

Average light intensity, measured in $\mu\text{mol}/\text{m}^2/\text{s}$, was above $80 \mu\text{mol}/\text{m}^2/\text{s}$ which has been shown to be the minimum value required to promote mating in adult BSF (Zhang et. al. unpublished). Mating was observed in the adult population of cycle six and the lighting array was not used until cycle seven. The complete photon flux data set can be viewed in Appendix G.

Initially both the UV-A and the metal halide lamps were used simultaneously but the flies were strongly attracted to the UV-A lamps. The attraction was so strong that the majority of the flies that landed on the bulbs died there. The reflector assembly of the UV-A light became covered in BSF carcasses. Operating the UV-A bulb was therefore

discontinued shortly after adult emergence during cycle seven. After discontinuing the UV-A light, the adults seemed to behave normally.

Insect vision is known to be faster than human vision so it is possible that the fluorescent light source used, cycling at 60 Hz, did not appear as a continuous source of light to the adult BSF causing unintended behaviours. Another possibility is that the light source wattage was too high for its location: 80 watts at less than 1 meter could be too intense for the adult BSF. This could not be measured with the photon flux meter because it was limited to the visible light range.

The wattage of the UV-A light source was selected based on the percentage of UV-A light in sunlight, approximately 8.5%², and because the light source was a 1000 watt bulb, an 80 watt UV-A light source was selected. There was no guidance in the literature about the intensity or range of UV wavelengths that stimulate BSF mating behaviours.

Although the use of the UV-A light source was discontinued, the documented role of UV-A in insect vision and the strong response of the adults to the light source suggests that further research is necessary to determine the particular wavelengths of light in the UV-A spectrum and their intensity that positively affect adult BSF mating behaviour.

This knowledge could greatly facilitate mating in commercial facilities and would eliminate the reliance on sunlight, which is greatly reduced during winter months in northern climates and can be obscured by cloud cover, to stimulate mating. Because newly emerged adults only have a narrow time span to mate, a system that could stimulate their mating behaviour with artificial light sources would be more reliable than one based on sunlight.

The 1 kW bulb continued operating throughout the winter months on a 12-hour cycle without interruption. Adults were observed to quest, mate and eventually lay eggs. The average photon flux observed by the meter varied in each cycle but the levels appeared adequate to propagate the colony. Not further lighting adjustments were made and

²<http://www.apogeeinstruments.com/spectroradiometer/improvinguv.html>

lighting system was shutdown in May of 2011. Figure 24 shows the photon flux recorded outside and inside the adult cage versus time.

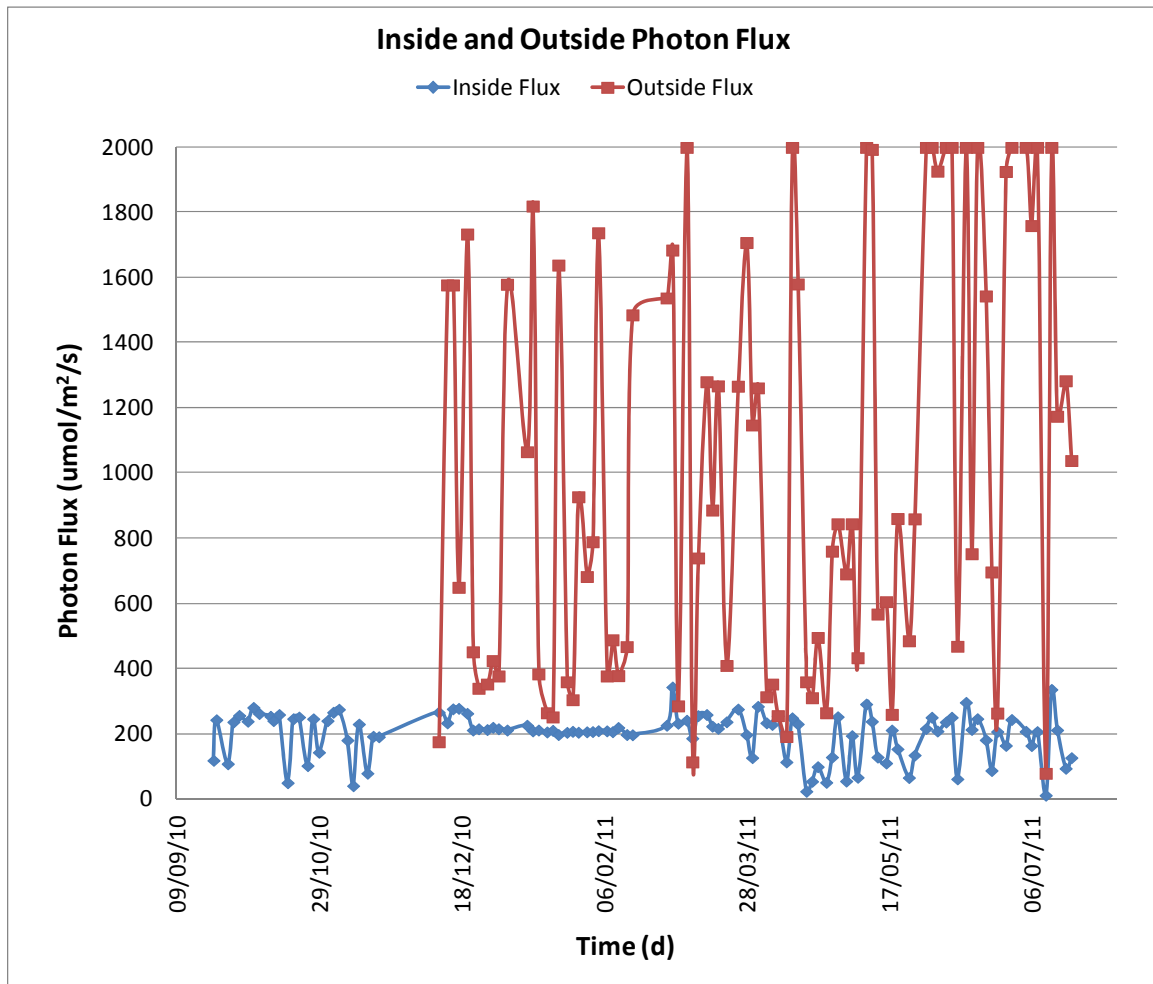


Figure 24 - Internal and External Photon Flux

The artificial lights were operated during the period on the graph between 18/11/10 through 01/04/11. The variations in light levels represented in blue are absent during this period. This is expected because of the light's operation. The light bulb reached full intensity in about one minute and remains at that level until it is shut off. Natural sunlight does not behave in this fashion: the intensity peaks and wanes gradually as shown in red. The effects of this difference and how they affected the BSF are presently unknown.

3.9.3 Hatchery

The changes implemented to the hatchery reduced the number of egg masses laid in unfavourable locations within the hatchery to zero in all remaining cycles. All of the observed egg masses in the hatchery were located inside the plastic egg flutes. There was however an unforeseen problem. The egg laying sites (the plastic flutes) occupied the entire opening between the hatchery and the RS; the flutes butted up against the framing of the adult space wall as shown in Figure 25.

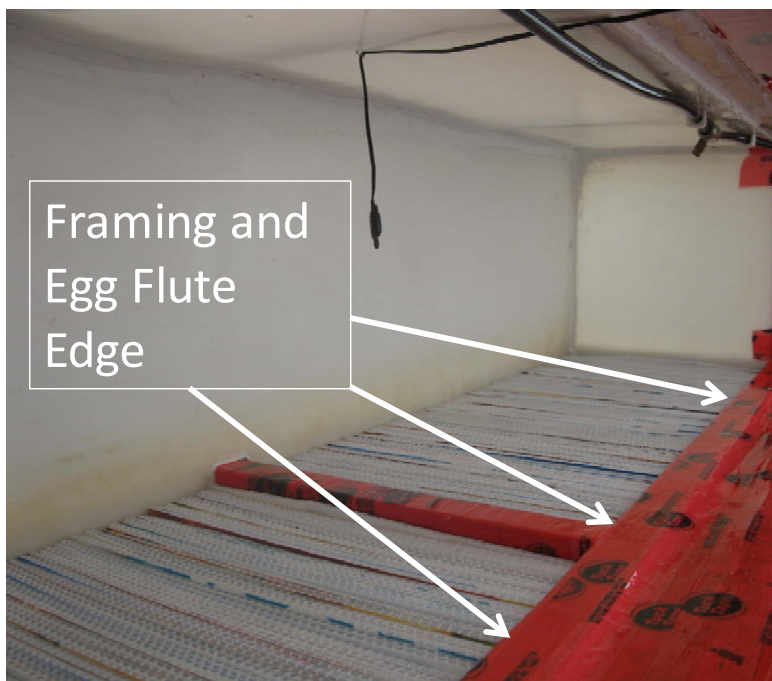


Figure 25 - Proximity of Framing to Egg Flutes

The proximity of the flutes to the framing allowed freshly eclosed maggots to migrate away from the hatchery towards the adult space not the RS. Large numbers of hatchlings were observed crawling along the walls of the adult space. Attempts were made to collect these individuals but the majority were lost in unknown quantities. The hatchery was therefore redesigned to include a wire mesh basket and the plastic flutes were placed inside. These baskets were attached to the pre-existing frame of the hatchery creating a space that hung 0.203 m below the adult space frame. In this design

the freshly eclosed maggots would fall into the RS before they had a chance to escape into the adult space. The cage design is shown in Figure 26.



Figure 26 - Hatchery with Hanging Basket

The old egg cartridges were cut in half and placed in an upright triangular position (as opposed to horizontally) exposing both sides of the flutes to the adults (not shown). This setup was employed for cycles seven and eight.

No further escapes were observed with the new system design. Placing the eggs flutes at an incline ($\sim 45^\circ$) also increased the available egg laying sites and allowed excess water from the misters to drain instead of collecting on top of the egg cartridges. The egg cartridges should be oriented vertically in any future versions.

3.10 Major Operational Issues

Although the system functioned as intended there were some operational issues that prevented ideal conditions and presumably peak efficiencies. Optimal environmental conditions were difficult to maintain over the course of this research. Temperatures were often outside of the optimum range in the summer months and optimal humidity

levels were difficult to maintain year round, this was most likely the result of the greenhouse construction. The variability in temperature caused by the double greenhouse infrastructure was the cause of many setbacks.

The location of the system, inside two greenhouses, greatly complicated efforts to cool the facility in the summer. The greenhouse scenario was chosen because of its availability but exposure to sunlight is only relevant for the adults; in fact, a “full” greenhouse enclosure is not necessary. Even in the adult room, full transparency to light likely is not required; observations of adult behaviour showed that adults will actively seek out a light source. Instead of full greenhouse construction all that is likely required is a window permitting sunlight to enter throughout the day. The size of this window would depend on the number of adults present and the space available: the design relationships for this window were not researched. Based on these observations the ideal housing structure could be a hybrid facility consisting of a greenhouse for the adult space and a separate covered and insulated building for the maggots to process waste.

The change in construction should improve energy efficiency and help stabilize environmental conditions from those experienced in the double greenhouse setup which caused most of the BSF maggot and adult casualties and subsequent problems.

It was also challenging to contain both the maggots and the adults. The water collection system ultimately contained the maggots effectively. To improve maggot containment the feeding space should be constructed as one solid piece from a corrosion resistant material, preferably from non-reactive plastic or a corrosion resistant non-leaching metal.

The adults can be contained with proper construction materials and techniques. The adult space will require the use of materials that have smooth surfaces and can form seamless joints with other surfaces to prevent egg laying in unwanted locations and to permit easy cleaning. This smooth crevice-free surface requirement should also be applied to any equipment or structures within the adult space. Plastic in rolls, such as

those used in vapour barriers, were found to perform satisfactorily for this purpose. Seams and joints should be sealed with silicone or another sealant that remains flexible throughout its lifespan. Acrylic caulking is not recommended because it cracks and forms crevices.

Mammalian and avian pests were originally expected to pose problems but did not during the course of study. Proper processing and handling of the food waste prevented such nuisance elements. The food waste was ground up, mixed with water and stored in five gallon air tight buckets. This deterred cats, rats, mice and raccoons– which were all present at the landfill – from seeking out the food waste. Parasitic pests were not seen to attack the feeding maggots and housefly populations were non-existent, except when the BSF maggots suddenly died from environmental variables. This further demonstrated the ability of BSF maggots to exclude other fly species from a food source and thereby restrict their propagation.

However, several pest species did eventually saturate the pupation medium. The pupating maggots, and the remaining pupal casings, are a food source for various other organisms including beetles, worms, aphids and spiders. Repeated observations suggest that only the worms were detrimental to the pupa and the emerging adults.

Plant life should also be considered in the adult space. Adult males have been shown to claim spaces on plants and use them as a launching pad during aerial questing (Tomberlin and Sheppard 2001). A natural setting will likely encourage and assist the effectiveness of the mating cycle.

3.11 Design Changes and Preparation for Batch Operations

The end of cycle eight marked the end of the system's operation in the continuous mode. After its end all of the BSF biomass was removed from the facility. The system was cleaned and any eggs in the cartridges were weighed which provided the first

isolated opportunity to estimate the mass of eggs produced by a cycle. It also revealed a difficulty with the data collection method: the egg cartridge assemblies were too heavy and large to measure with the available scale. Because no other scale was readily available, new and smaller egg cartridges were assembled measuring 50 mm L x 50 mm W x 25 mm H. The flute dimensions were not affected. Sixty-four cartridges were installed in total, 32 in each of the hatchery divisions.

A humidification system that was controlled separately from the greenhouse humidification system was installed in the hatchery to help maintain hospitable conditions. This system used the hot exhaust air from the 1 kW light's cooling fan. The air was circulated through a plenum where two ultrasonic misters atomized water adding moisture to the air which was then redirected back to the hatchery via a 2-inch diameter ABS perforated tube. These changes made the hatchery more hospitable in the winter for the sensitive eggs and reduced the need for frequent operator intervention, such as adding moisture, moving eggs and so forth, which could impact the system.

After cycle eight the system was shut down, cleaned and minor overhauls were made to subsystems. No significant design changes were implemented.

Chapter 4 Batch Operations

4.0 Batch Operations

Operating the system in the continuous mode demonstrated that the BSF species could be propagated in artificial conditions during the winter months in northern climates. In many ways, this would emulate a working system that processed waste and generated BSF maggots which could then be used for secondary application, such as livestock feed.

The next set of experiments operated the system in “batch” mode – or one BSF grouping (or cohort) at a time to determine if the species was more efficient at waste reduction with only one cohort present at any given time in the reactor and if operation of a facility would be more practical using this approach. A batch operation allowed for easier measurement of operational variables because life cycle stages were easier to identify with little to no overlap between different cohorts.

4.1 Methods

The data collected from the RS and the methods used to collect them were same as those in the continuous set of experiments. One notable difference in this operation was the way eggs were handled.

After eggs were laid in the cartridges they were brought to the University lab for measurements and incubation until they hatched; this operation typically lasted one week before they were returned to the landfill facility. During this one-week period the newly hatched maggots were fed a diet of chicken feed. This change in procedure was necessary to accurately measure the mass of eggs obtained from each cycle. The eggs were then incubated to minimize their handling before returning the one week old larva to the landfill.

The first of four batch runs commenced on February 2, 2011 with the addition of freshly eclosed larva.

4.2 Observations

No significant differences were noted from previous operations. Maggots continued to consume waste and migration was observed as expected. The collection of waste residue proved simpler and it was easier to determine when the feeding and migration cycles ended. As expected, the population increased between cycles one and two because of the nature of the flies' reproductive strategy but the increase was modest. Adult behaviour appeared normal (aerial questing and mating pairs were observed) at the end of cycle one but no eggs were visible during the time when eggs were expected to be laid. It was originally thought that the ambient conditions (high temperatures and low humidity) were forcing the gravid (egg carrying) females to delay egg laying until favourable conditions were present.

Searching the adult space revealed that egg laying had in fact been occurring but not in the hatchery. Instead, the majority of eggs were found in the crevices around the pupation medium and in the southeast corner of the adult space on the floor. By the time the eggs were discovered, some of them had already hatched and reached their second or third instar phase. The nutrition source used by these hatchlings was not determined. All of the found eggs were collected and taken to the university lab for processing; the hatched maggots were also collected but many escaped or were killed during this attempt. The survivors were placed in the reactor space.

Cycles one and two appeared to operate normally although the number of maggots present was less than expected. Cycle three began on May 24, 2011. During this cycle the number of maggots and eggs recovered decreased despite searches in the adult space for eggs. Because there did not appear to be any other explanation, it was assumed that the exceedingly high temperatures reached in the facility ($>50^{\circ}\text{C}$) and the inability of the cooling systems to dissipate heat affected the amount of eggs collected in cycle three.

This trend continued into cycle four when the colony crashed and died after approximately two years of successful operation. The immediate cause of the crash was a failure in the ventilation system towards the end of batch cycle four. The main inner greenhouse fan suffered a bearing failure causing the fan to stop operating which in turn allowed the temperature in the inner greenhouse to exceed 60°C. Although some adults remained alive and eggs were found, the temperatures reached were too great for the colony to recover. The collected eggs were incubated but none hatched and the remaining adults failed to lay new eggs. The amount of eggs collected suggest that if the mechanical failure had not occurred the colony may have rebounded from the losses suffered in batch cycle three.

4.3 Results and Discussion

The operation of the system in batch mode meant that only one cohort was present in the subsystem at any given time. Cycles one and two operated with few issues during the feeding and migration stage. During the adult phase of cycle one, for the first time in the system's operation, egg laying was observed in areas outside the hatchery in significant quantities. It was originally thought that egg laying was not occurring at all due to variances in ambient conditions. This was determined to be incorrect after eggs were found outside the hatchery in various locations in the adult room including the floor, the pupation chamber and in crevices. Another possible reason for the change in the egg laying location was thought to be the absence of an attractant in suitable quantities below the hatchery. During continuous operation maggots were actively feeding underneath the hatchery and it was presumed that this activity would draw female adults to the area to lay more eggs.

Approximately 12.7 kg of food waste was added underneath the hatchery during cycle two but this did not affect the egg laying preference of the adult flies. Although some eggs were laid in the hatchery, most were located near the pupation chamber in the seams of its construction. A suitable explanation for the adult's avoidance of the

hatchery or preference for another egg laying site was not determined until late in cycle two when egg laying overlapped with maggots that were still feeding; egg laying resumed in the hatchery but only briefly.

It is hypothesized that adults are not only attracted to the volatiles emitted by rotting food but also to the presence of actively feeding maggots. Further research is needed to determine if this incident was a coincidence or if the maggots were truly responsible for the attraction of adults to the feeding site. If this is indeed the case, the batch operation may need to be reconfigured to allow for such an attractant to restrict egg laying to desired locations.

It was also observed that the parasitic worm population was increasing. The pupation chamber was demolished and replaced. The new pupation chamber was a plastic storage bin with a capacity of 0.751 m³. The same type of pupation medium was used in the new setup and plastic construction eliminated the fine crevices and seams present in the old pupation chamber. The lack of these crevices should help deter pests from entering into the new pupation chamber.

4.3.1 Reactor Space

A summary of the data collected in the RS is presented in Table 9.

Table 9 - Reactor Space Data Summary Batch Cycles 1, 2, 3 & 4

Reactor Data											
Cycle	Start Date	End Date	Length (d)	Avg Temp (C)	Estimated Max Mag #	Std Dev	Dry Mass Given (kg)	Dry Mass Leftover (kg)	% Reduction	Avg Dry Consumption Rate (g/mag/d)	Std Dev
1	18/02/11	28/03/11	39	30.7	23405	9605	15.7	11.2	27.8	0.017	0.037
2	13/04/11	17/05/11	37	30.2	36454	8830	28.9	11.7	57.0	0.023	0.024
3	24/05/11	03/06/11	11	27.3	6254	1766	3.8	2.4	36.1	0.044	0.036
4	06/07/11	20/07/11	15	34.3	5828	1060	8.8	6.3	27.6	0.062	0.025

The most striking difference between the batch and continuous operation is the number of maggots obtained. The increases between cycles one and two are modest at best

whereas the increase at the corresponding point in the continuous operation was nearly five-fold. Waste reduction and consumption values are comparable to that in the continuous mode. The crash of the colony after only four cycles of batch operation makes further comparisons difficult and as such, reliable conclusions about which operational mode is more efficient cannot be made at this point.

The final average waste consumption rate in cycle four is abnormally high. This is because the number of maggots in this cycle was extremely low compared to the other three cycles but the waste was not fully digested. However, cycle four values are included for the sake of consistency. The decline of the colony due to heat stress is evident starting in cycle three and the waste consumption rates are shown in Figure 27. The individual curves of cycles one and two show similar trends but there is an unexpected dip in the waste consumption rate followed by a slow rise in cycle two: the cause of this dip is not known.

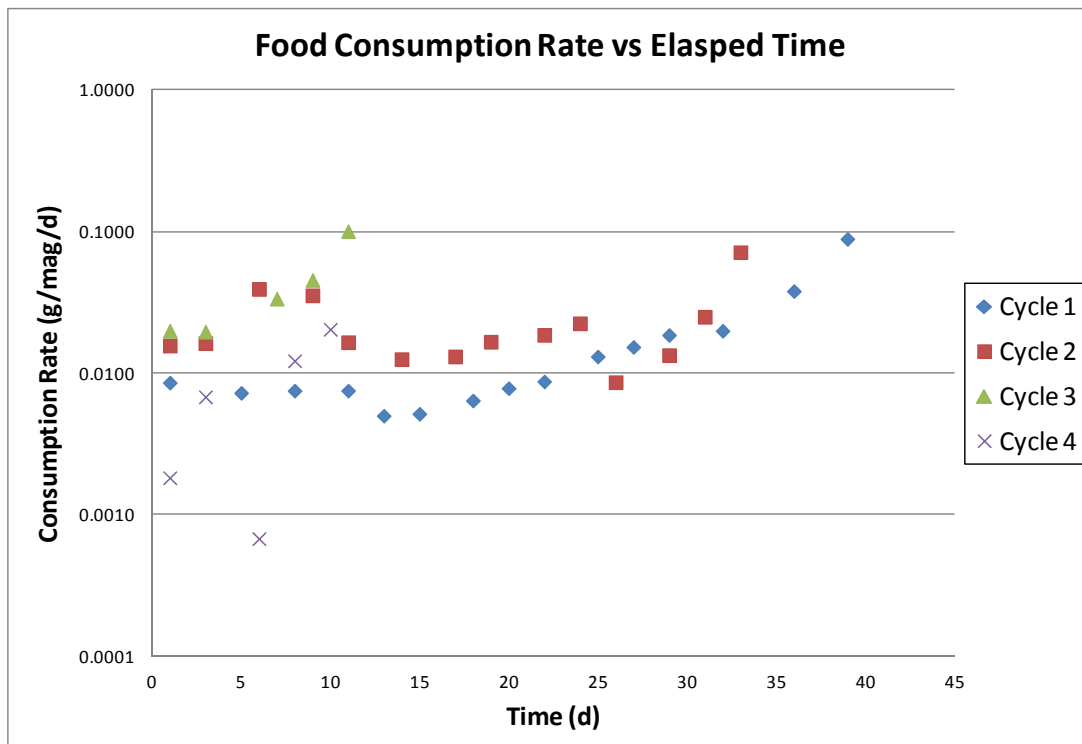


Figure 27 - Batch Waste Consumption Rates

The number of maggots in each cycle is shown in Figure 28.

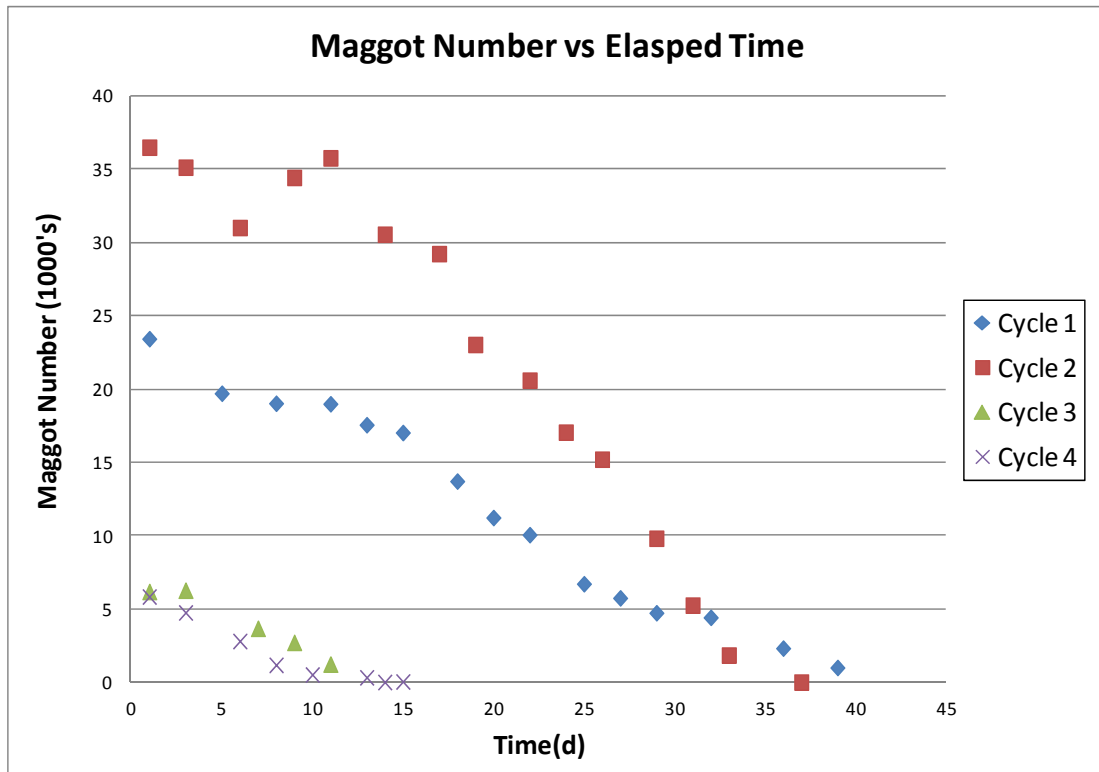


Figure 28 - Estimated Maggot Number Batch Operations

The trend in the batch operational mode is different from that of the continuous operation mode: maggot numbers start high and gradually decrease because of outward maggot migration. This is a different profile than that in the continuous operations graphs of maggot numbers. Possible explanations for the observed maggot number trends in the continuous operational phase were described in Section 3.6.2. During batch operations the experiments were better controlled and the reactor was thoroughly cleaned between cycles so that elusive maggots had no places to hide. Also, because the hatchlings were incubated at the University's lab and not placed in the reactor space until they reached a readily visible size, sampling and counting errors were reduced significantly. This profile is therefore expected to more accurately represent the maggot number trend in a reactor when no additional influx of maggots from hatchlings is present.

4.3.2 Adult Space

Table 10 summarizes the data for the adult space during the batch operations.

Table 10 - Adult Space Data Summary Bacth Cycles 1, 2, 3 & 4

Adult Room & Hatchery Data															
Cycle	Avg. Temp (C)	Avg. Humidity (%)	Avg Light Levels (umol/m2/s)	Hatchery Avg. Temp	Hatchery Avg. Humidity	Total Mass of Mag Leaving (g)	Mag Exit Ratio (W:B)	Mag # Check	% Diff. from Reactor Est.	Egg Mass (g)	Est. Egg #	Est. Clutch #	# of Mating Adults	# of Adults Emerged	% of Mating Adults
1	32.7	59.4	242	31.9	34.3	2335	1.59	15261	34.8	21.019	1070582	2698	5397	7631	71
2	29.9	35.6	145	26.5	27.3	3906	0.25	25529	30.0	6.338	322820	814	1627	12765	13
3	32.0	36.2	175	29.5	28.2	527	16.13	3444	44.9	0.201	10238	26	52	1722	3
4	33.5	44.7	165	31.3	37.4	352	1.58	2301	60.5	3.095	157641	397	795	1150	69

Cycles one and two show the highest numbers of produced eggs. In cycle one the average humidity was 59.4% in the adult space. At the same time, the egg yield was high relative to the number of maggots entering the system. Contributing factors could be the humidity level, which for cycle one was the closest to the optimum range in the entire batch trials, and the average temperature was also in the proper range. Average light levels were also in the appropriate range. The results from this cycle strongly support the need for proper control over the environmental conditions and their effect on the adult stage of the BSF.

The egg masses collected at the end of cycle four suggest that the colony could have rebounded from the ventilation system's failure. The increase in collected eggs was approximately fifteen-fold. Although the fan was repaired it was unable to meet the cooling needs of the greenhouse. The external temperatures raised temperatures in the greenhouse to levels where the cooling system could not remove a sufficient amount of heat. In all likelihood, this heat killed the collected eggs from cycle four. The eggs were taken to the university but all failed to hatch.

The failure of the ventilation system in cycle three is marked by the low mass of eggs collected. The average temperature does not reflect the spikes in temperature. A high

temperature outside the tolerable range cannot be tolerated by the adult for a long time – a short duration is sufficient to inflict damage. The maggot exit ratio also suggests that the maggots in the RS suffered during the temperature spikes.

The ambient conditions in the adult space between the first two cycles and the final two are illustrated in Figures 29 and 30. Figure 29 shows some instances where the temperature exceeded 45°C, which is above the high range (33°C) of the optimal temperature range. This occurred at least five times during batch cycles one and two. Despite these temperature exceedances the adults were able to complete their life cycle and provide eggs for cycle three. Figure 30 shows that the temperature in cycles three and four. Cycle four had more instances where the temperature exceeded 45°C and 50°C.

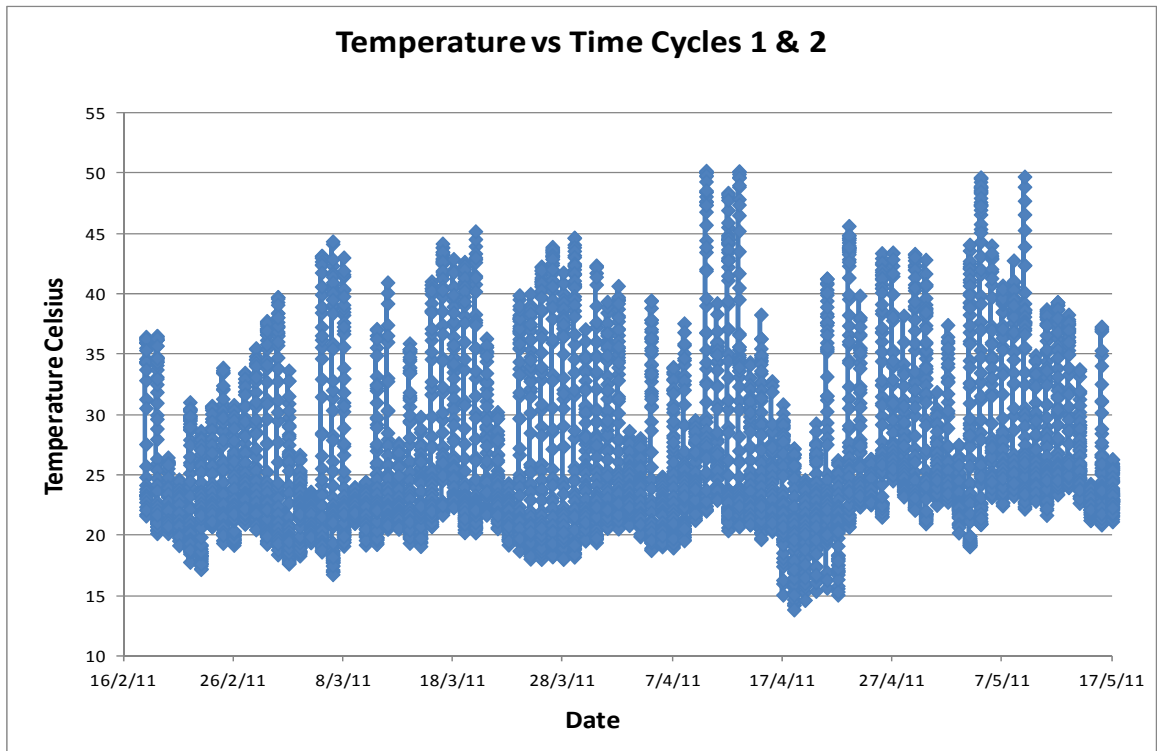


Figure 29 - Temperatures Batch Cycles 1 & 2.

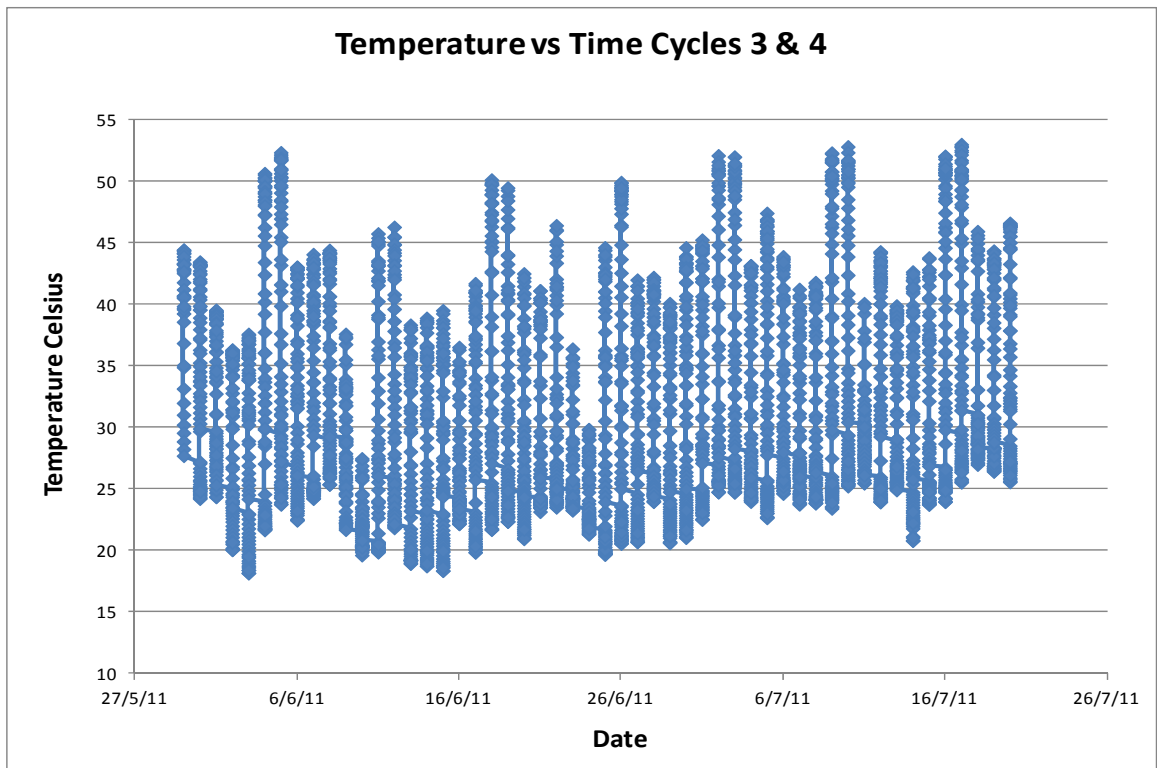


Figure 30 - Temperature Batch Cycles 3 & 4.

The end of cycle four marked the end of the colony and operations at the EWSWA facility.

Chapter 5 Overall System Evaluation and Conceptual Design

5.0 Overall System Evaluation

In the previous sections the system was examined in stepwise fashion to show its design progression. However reviewing all operations can determine the overall performance and allow for the assessment of other important design parameters. The most important system operations occur in the RS and the adult space.

Although the system was operated in two different operational modes, continuous and batch, all data was treated as one superset and the necessary parameters were derived from both sets of data. This was done to obtain the best possible averages from the data and despite the different operational modes, the data sets appeared similar with a high degree of overlapping ranges for most measured parameters. Overall data summaries for the reactor space, the adult space and the hatchery are in Appendix H.

5.1 Reactor Space

The overall data set is shown in Table 11. Cycles 1 through 8 represent continuous mode operation; the second set of cycles 1 through 4 represent batch mode operation.

Table 11 - Overall Data Summary Reactor Space

Reactor Data											
Cycle	Start Date	End Date	Length (d)	Avg Temp (C)	Estimated Max Mag #	Std Dev	Dry Mass Given (kg)	Dry Mass Leftover (kg)	% Reduction	Avg Dry Consumption Rate (g/mag/d)	Std Dev
1	13/01/10	19/02/10	38	24.1	25937	6135	13.2	8.3	35.3	0.039	0.035
2	26/02/10	01/04/10	35	26.6	101209	11849	82.3	37.4	52.3	0.027	0.009
3	02/04/10	28/04/10	27	28.1	34749	6299	6.6	4.1	36.1	0.028	0.037
4	30/04/10	21/06/10	53	26.0	331236	40346	107.3	40.2	60.1	0.022	0.014
5	23/06/10	12/07/10	20	30.8	13314	7273	2.2	1.2	43.9	0.021	0.028
6	23/08/10	20/09/10	29	22.0	10680	5955	5.5	3.3	37.8	0.029	0.011
7	22/09/10	19/11/10	59	20.6	111544	21578	50.4	18.7	60.3	0.015	0.008
8	22/11/10	31/01/11	71	20.0	184230	85262	23.3	10.9	51.0	0.008	0.008
1	18/02/11	28/03/11	39	30.7	23405	9605	15.7	11.2	27.8	0.017	0.037
2	13/04/11	17/05/11	37	30.2	36454	8830	28.9	11.7	57.0	0.023	0.024
3	24/05/11	03/06/11	11	27.3	6254	1766	3.8	2.4	36.1	0.044	0.036
4	06/07/11	20/07/11	15	34.3	5828	1060	8.8	6.3	27.6	0.062	0.025

Throughout the course of the research approximately 350 kilos of food (dry weight) were consumed by the maggots over twelve operational cycles. The maggots generated approximately 156 kg of dry residue. The overall average food (waste) reduction was approximately 44% +/- 12. The average dry matter consumption rate for the system's operation was estimated to be 0.028 (g/mag/d) +/- 0.023. The high spread of the data is likely due to the variability introduced by the changing number of maggots between each cycle and the area measurements of the feed pile.

This variability is hypothesized to be an intrinsic characteristic of a naturally propagating the colony. Under ideal conditions the population would continue to increase unless a certain amount of prepupae were removed from the system in a controlled setting. In natural surroundings, external factors (predation, disease, etc.) would limit population growth. Observed increases suggest that this prepupae harvest could be as high as 97% of all prepupae collected. This is advantageous because it suggests that the bulk of the prepupae can be used as removable, value-added product and not needed to propagate the next generation.

This circumstance is most likely the result of the BSF's reproductive strategy; in natural conditions large numbers of eggs are laid to improve the chances of successful gene transfer to the next generation and not all prepupae will survive. The harvest capacity estimate was meant to quantify this value. However, further research is needed to adequately quantify the harvesting capacity or sustainable yield of this system.

To determine if any similarities in maggot number trends existed during a cycle's progression, all eight continuous mode cycles were graphed as shown in Figure 31. Batch mode cycles are not included.

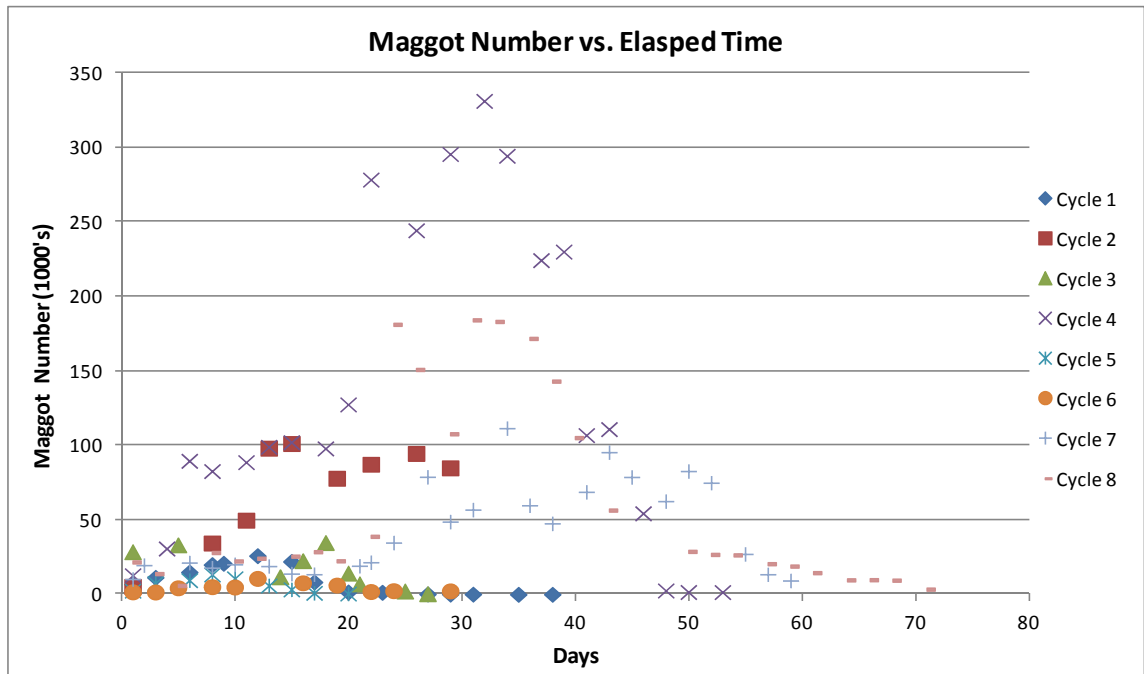


Figure 31 - Estimated Maggot Number Graphs Overlapped

Cycles two, four, seven and eight produced the highest number of maggots. Cycles four, seven and eight seem to follow a similar pattern of a sharp increase, followed by a decline before the eventual maximum value was attained. The reason for this trend is unclear but a possible explanation could be that the initial decrease is the result of the start of outward migration by maggots and the following increase could be the result of freshly eclosed maggots in the reactor space. Cycle seven appears to show two events of decrease and increase. It is possible that cycle seven is in fact two cycles or that conditions in the hatchery caused a delay in hatching for some eggs.

It is also possible that the dips are merely errors in data given the high variability of the results. Despite the variability in the data, one trend is clear: the maggot population from all eight continuous cycles seemed to exhibit a sharp increase before finally levelling out. This increase however could just be a phenomenon related to the manner in which the maggots were sampled or due to overlapping cohorts between cycles.

The exact importance of these trends to an operating facility is unclear but it may affect the application rate of waste: the lower number of maggots present in the system could

impair its ability to process waste. It can also be seen in Figure 31 that cycles one, three, five and six had comparatively low but consistent maggot numbers.

The continuous operational cycles were then charted chronologically. Shutdown periods were omitted. The results are shown in Figure 32.

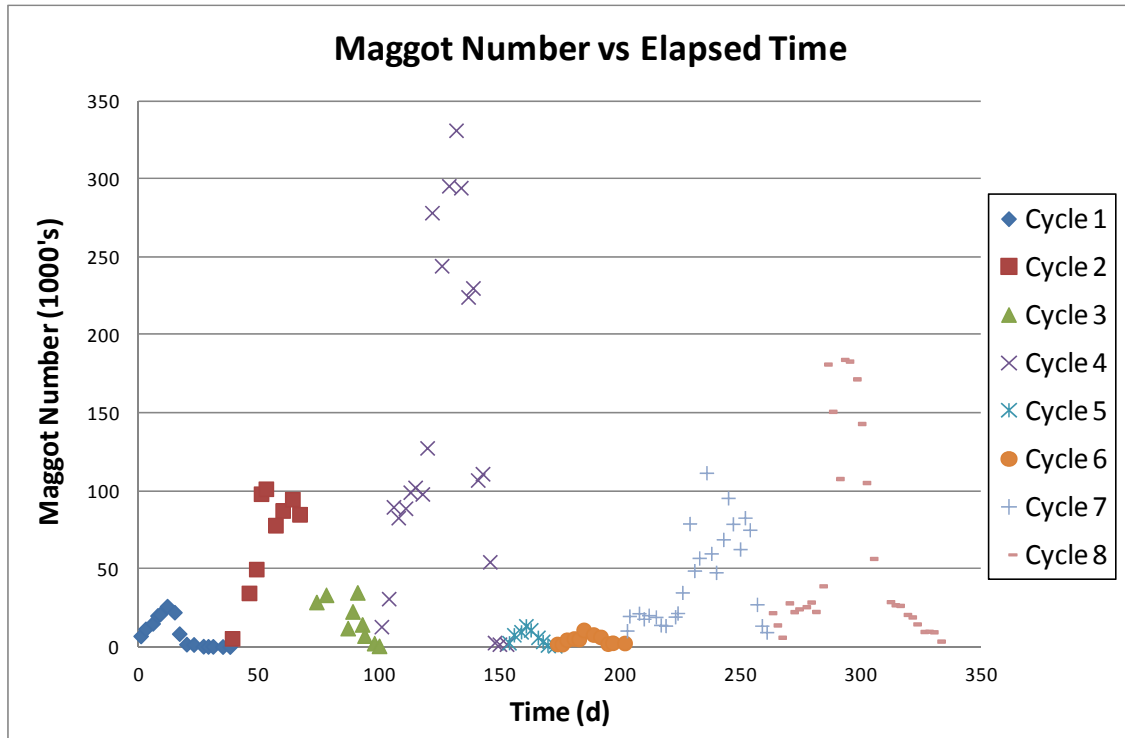


Figure 32 - Estimated Maggot Number in Consecutive Order.

Figure 32 shows the increase in maggot numbers from one cycle to the next. The most substantial increase between cycles was evident between cycles three and four. The reasons for this increase are thought to be the result of factors in the adult space and hatchery. However, a review of the data during cycle three's adult stage does not immediately reveal any special circumstances. The adult stage occurred in early to mid-May of 2010, relative humidity was 37.7% and the average temperature was 31.8°C. Unfortunately at this stage in the research the ambient light levels and egg masses were still not measured so a definite conclusion on the role of abiotic factors could not be reached.

There is another modest increase that occurs between cycles seven and eight but it is only two-fold. The average ambient visible light level for this adult stage was 202 $\mu\text{mol}/\text{m}^2/\text{s}$ and relative humidity was 39.7% and temperature was 29.3°C. Egg masses were not collected at this stage. What is also unclear is the role of genetic variability and inbreeding; the colony was never mixed with outside BSF for the entire course of the research. After several successive generations, the effects of inbreeding may have hampered the ability of the colony to propagate itself with the same vigour in later cycles as it did in earlier cycles.

5.1.1 Average Daily Dry Waste Consumption Rate and Waste Loading Rate

The average daily dry waste consumption rate is the basis of the design for the reactor space and by consequence, any future facility. The basis for the consumption rate was the estimate of the maggot number and how much waste they consumed in a certain amount of time. However, the metrics used to calculate the consumption rate varied substantially. The number of maggots present in the reactor space at any given time is not static. The area and depth of the food waste were also not static and changes were observed daily. The number of maggots also differed from one cycle to the next. This variability was carried forward to all other design parameters that depended on the waste consumption rate. For future studies that attempt to refine the food consumption measurement, the experiments should use smaller reactor vessels that allow the food to cover the entire surface area. In this way, a single dimensional reading, the depth of the food pile, can be more easily managed and measured.

In addition to the system's waste reduction capabilities, a waste-loading rate should also be specified. Before this value can be calculated however, some basic assumptions were made.

- 1.) Based on observations from this research the maggots were observed to feed in a single layer in what was termed the **preferential feeding position**. As a result,

- 2.) Assuming that the maggots would be in a vertical position, an estimate of their cross sectional area was estimated. Based upon visual observations, the cross sectional shape of a maggot body was modelled after an ellipse and the maggot's cross sectional area was calculated using the following formula, where variables (a) and (b) are one half the lengths of the major and minor axes respectively:

$$\text{Eqn. (9) - Area of ellipse} = \pi ab$$

In order to determine suitable values for (a) and (b), eighty maggots were collected and their body's length, width (a) and thickness (b) were measured. Body measurement data are available in Appendix I. The average cross sectional area was then determined to be $0.13 \text{ cm}^2 \pm 0.04 \text{ cm}^2$. The average cross sectional area of one maggot was then used to determine the number of maggots that would fit into 1 cm^2 . The waste processing capacity of 1 cm^2 was determined using the average dry matter consumption rate per maggot per day. The results were then scaled to units of $\text{kg/m}^2/\text{d}$; these values are shown in Table 12.

Table 12 - Application Flux

Dry Waste Application Flux		
(g/d/cm^2)	0.2	0.2
$(\text{kg/d/m}^2) \text{ (Eqn 10)}$	2	2

The effects of the maggot number variability in the reactor are visible in the application flux as indicated by the standard deviation. A study published by Diener et. al. (2009) however shows similar results of 3 to $5 \text{ kg/m}^2/\text{d}$ for market waste.

Although the spread of the data would indicate that at some point the application rate is zero, this is most likely not the case. With the observed population numbers it is highly improbable that there would not be a demand for feed during the food consumption stage. The only situations where the application rate may be zero are if the system was previously overfed or if the entire maggot population died from unforeseen circumstances.

5.2 Adult Space and Hatchery

The complete data set for the adult space and hatchery are shown in Table 13.

Table 13 - Overall Data Summary Adult Space

Adult Room & Hatchery Data															
Cycle	Avg. Temp (C)	Avg. Humidity (%)	Avg Light Levels (umol/m2/s)	Hatchery Avg. Temp	Hatchery Avg. Humidity	Total Mass of Mag Leaving (g)	Mag Exit Ratio (W:B)	Mag # Check	% Diff. from Reactor Est.	Egg Mass (g)	Est. Egg #	Est. Clutch #	# of Mating Adults	# of Adults Emerged	% of Mating Adults
1	NR	NR	NR	NR	NR	1743	2.27	11392	56.1	NR	NR	NR	NR	5696	NR
2	22.2	21.0	NR	NR	NR	4833	1.08	31588	68.8	NR	NR	NR	NR	15794	NR
3	31.8	37.7	NR	NR	NR	1712	0.90	11190	67.8	NR	NR	NR	NR	5595	NR
4	31.9	31.5	NR	NR	NR	9817	2.05	64163	80.6	NR	NR	NR	NR	32082	NR
5	35.6	26.3	NR	NR	NR	1245	2.27	13314	38.9	NR	NR	NR	NR	6657	NR
6	31.2	42.9	195	27.3	34.1	796	2.47	5203	51.3	NR	NR	NR	NR	2601	NR
7	29.3	39.7	202	27.0	32.1	6445	4.56	42124	62.2	NR	NR	NR	NR	21062	NR
8	28.1	30.8	208	27.0	26.1	7391	3.99	48307	73.8	14.706	749036	1888	3776	24154	16
1	32.7	59.4	242	31.9	34.3	2335	1.59	15261	34.8	21.019	1070582	2698	5397	7631	71
2	29.9	35.6	145	26.5	27.3	3906	0.25	25529	30.0	6.338	322820	814	1627	12765	13
3	32.0	36.2	175	29.5	28.2	527	16.13	3444	44.9	0.201	10238	26	52	1722	3
4	33.5	44.7	165	31.3	37.4	352	1.58	2301	60.5	3.095	157641	397	795	1150	69

Assessing the parameters in the adult stage proved more difficult because they move in three dimensions and they have multiple activities to perform in this life stage. As larvae their concern is finding a food source and consuming it; as adults, their concerns are to find water, a mate, copulate and lay eggs. Their life span is also shorter than the larval phase. The main goal of the female adults is to produce the largest amount of eggs possible. The parameters most needed for facility design would therefore be the number of adults present, the number of mating pairs present, the number of egg

clutches laid, and the finally the number of eggs in a clutch. The method to determine the number of adults present was described in Section 3.4. This approach however proved impractical because of the adult's mobility and their spatial distribution in the available surface area.

The approach was therefore modified from proactive to retroactive; instead of counting the adults present, the number of mating pairs had to be estimated from the amount of eggs produced. This was accomplished by using the total mass of eggs collected from a cycle, knowing the mass of one egg, the number of eggs in a clutch, the number of clutches present, and then comparing this value to the total number of collected maggots entering the pupation medium.

Because some of the necessary egg mass and clutch data was not collected in this research, data from Nguyen (2010) was used due to similar diet and exposure to greenhouse conditions: the data are also presented in Appendix I. Ninety-one sample egg clutches were weighed and the numbers of eggs present in each clutch were counted. Using these data the average weight of an egg and clutch were determined. The results are presented in Table 14.

Table 14 - Egg Mass Data

Average Weight of		Average Weight of	
One Clutch		One Egg	
(g)	Stdev	(g)	Stdev
0.00779	0.00512	0.0000196	0.0000048

These data were then used to estimate the number of egg clutches, eggs present for each cycle, the number of mating pairs and the number of mating adults from recorded eggs masses for a given cycle. The estimated number of adults present in the adult cage was estimated using the incoming number of pupa and assuming an emergence of 50% when relative humidity was 40% (Holmes 2010). The percentage of mating adults in the adult room was estimated with these data and the mass balance obtained in Section 3.0.2. The results were previously shown in Table 13.

It is still not readily clear how much volume questing adults need to mate successfully and what density of adults is optimal for mating behaviours. However, a reasonable estimate can be made from data collected during the mass balance experiments. In these experiments approximately 800 to 1000 adults emerged into cages measuring 1 m W x 1 m D x 1.5 m H or 1.5 m³. The mass of collected eggs, which represent the results of successful mating, are summarized in the following table.

Table 15 - Emergence Adult Density & Egg Masses from Mass Balance

100% Emergence Number of Pupal Casings	Adult Density (#/m³)	Total Wet Egg Mass Collected From Cartridges (g)
1040	693	4.261
593	396	2.376
673	449	2.730
634	423	3.894
952	635	4.575
924	616	4.325

Further to these results, data collected from the facility exhibit the following adult densities as shown in Table 16.

Table 16 - Adult Density and Egg Masses from Experiments

Adult Room & Hatchery Data			
Cycle	# of Adults Emerged	Adult Density (#/m³)	Egg Mass (g)
Continuous Operations			
1	5696	393	NR
2	15794	1089	NR
3	5595	386	NR
4	32082	2213	NR
5	6657	459	NR
6	2601	179	NR
7	21062	1453	NR
8	24154	1666	14.706
Batch Operations			
1	7631	526	21.019
2	12765	880	6.338
3	1722	119	0.201
4	1150	79	3.095

It appears that the largest recorded egg yields happened with adult densities of 526 and 1666 adults per m³. These values were averaged and the result was used in design calculations for the adult space. It is noteworthy to mention that this is a cursory estimate; abiotic factors were not considered in this estimation and further research is needed to determine optimal adult densities.

The shape of the adult space volume also remains in question although in both experimental setups, the mass balance and the facility experiments, the adult spaces were cube-like, other shapes may improve mating success. It is also hypothesized that the height of the adult space should allow for the upward flight patterns that males exhibit (Tomberlin 2001) during aerial questing for females. The role of flora in the adult space also deserves more study because no plants were used in these experiments.

5.3 Continuous versus Batch Operations

The optimal operational mode – continuous versus batch – could not be determined based on performance indicators studied in these experiments. However there are some advantages to batch mode (one cohort at a time). Maintenance for the system is greatly simplified in the absence of maggots. Although the maggots are robust, they have limits on their toxicity tolerance.

For example, during the processing of protein rich feeds the production of ammonia is evident and it must be removed to maintain optimal feeding conditions. Another advantage is the ability to isolate problems. For example, if a disease were to enter the reactor space, its effects could be contained to a single generation of BSF. These circumstances favour the batch operational mode over continuous operations.

5.4 Conceptual Facility Design

The following illustrates the conceptual design of a waste processing facility using BSF and is meant to outline how the various systems would be sized based on the

information collected during this research. The design equations are first presented in their most generic form and a case example using collected data follows. An example using collected data is deferred until the end of Chapter 6 after resource consumption is quantified.

Two conceptual design cases were considered:

- 1.) Where a building already exists; and
- 2.) Where a new building must be constructed.

These two design cases were considered because a retrofit of an existing building to serve as a BSF waste processing facility could be a common circumstance; this was the case at the EWSWA. However, the design of a new facility is also a possible circumstance and since the design approach would not change significantly, both circumstances were explored.

The basis for both designs is the dry matter waste consumption rate but the physical dimensions of the maggots, pupa, adults and eggs also affected the design of some of the subsystems. A spreadsheet that calculates the size requirements for the subsystems was constructed to facilitate the design of future systems: it can be viewed in Appendix H. To introduce flexibility and customization into the design, the survival rates of the maggots, the emergence rate of the adults, the mating percentage of the adults and the eclosion rate of the eggs are all adjustable parameters. The mass of one prepupa at the end of a cycle was assumed to be 0.153 g and is based on data collected by Nguyen (2010).

The facility design and its required parameters are based on the average cycle length of the feeding maggots. Although designs are typically done on a per day basis the cycle length was preferred for the following reasons:

- The high variability of the data, the effects of which were averaged out over the duration of the cycle;
- The system would not receive waste on a daily basis but on an as needed basis;

- Maggots do not continuously consume food: they can migrate away from the food source and return at a later time; and
- The facility's outputs would only be produced at the end of a cycle.

5.4.1 Design Case 1 – Use of an Existing Building

In the case where a building is already present and can be retrofitted for BSF to process waste, the application flux was calculated from the dry matter consumption rate and the number of maggots that would fit in one square meter (Eqn. 10). The application flux, or loading rate, was then used to determine the area required to process one ton of waste (Eqn. 11). The mass of maggots produced from this area was then calculated (Eqn. 12).

*Eqn. (10) – Application Flux (AF) (kg/d/m²) = (Avg. Dry Matter Cons. Rate per Mag) * (# of Maggots per Unit Area)*

*Eqn. (11) – Area Req. to Process 1 ton of Waste (ARPW) (m²) = 1000 kg / (AF * Cycle time)*

Eqn. (12) – Dry Mass of Mag. Prod. / Ton of Waste Processed (DMMPW) (kg) =

$$\frac{\# \text{Mag per unit area} * \text{ARPW} * \text{Mag survival rate} * \text{Mass per mag} * (1 - \text{moisture content of mag})}{1000000 \text{ mg/kg}}$$

The area required to produce one ton of maggots was also calculated: this area was termed a “reactor cell” (Eqn. 13). A one ton mass was chosen because maggots would be sold by the ton.

$$= \frac{1000 \text{ kg/ton}}{\text{DMMPW}} * \text{ARPW}$$

Next, the number of maggots that are present in one ton of maggots was calculated using (Eqn. 14).

Eqn. (14) – Maggot Number per dry ton (MP 1 Cell) (#) =

$$\frac{1 \text{ ton}}{\frac{\text{Mass of Prepupae \#/mg} * (1 - \text{moisture content})}{1000^3 \text{ mg/ton}}}$$

The result from Eqn. 14 is also the number of maggots produced from one cell. To determine the number of reactor cells that a given building area can house, an estimate of the adult space area requirement for one cell is necessary. The sum of these areas was termed a “system”. The result from Eqn. 14 was used to estimate the number of eggs required to sustain one reactor cell given the expected survival rate of the eggs. The calculation is shown in Eqn. 15.

$$\text{Eqn. (15) – Req. Egg \# (RE) (\#)} = \frac{\text{MP 1 Cell}}{\text{Egg Survival Rate}}$$

In order to proceed with the design an estimate of the average number of eggs in an egg clutch is necessary. Data collected by Nguyen (2010) indicates that this value is approximately 400 eggs per clutch +/- 252. Knowing that the average number of egg clutches is equal to the number of adult mating pairs, and that the number of mating pairs is one half the number of mating adults, an estimate of the number of adults required to produce the eggs can be calculated (Eqns. 16a, 16b, 16c & 17). This calculation also includes an estimate of the percentage of mating adults in a given population.

$$\text{Eqn. (16a) – \# of Egg Clutches for 1 Cell (EC) (\#)} = \frac{RE}{\text{Avg \# of Eggs in Clutch}}$$

$$\text{Eqn. (16b) – \# of Mating Pairs for 1 Cell (\#)} = EC$$

$$\text{Eqn. (16c) – \# of Mating Adults for 1 Cell (MA) (\#)} = 2 * EC$$

$$\text{Eqn. (17) – Req. \# of Adults for 1 Cell (RA) (\#)} =$$

$$\frac{MA}{(\text{fraction of mating adults in a colony}) * (\text{emergence fraction of pupae})}$$

Data about the fraction of mating adults in a healthy colony was not found in the literature for *Hermetia illucens* so an estimate of 50% was used. This value was chosen because it is the median value and most likely underestimates the percentage of adults mating thereby providing a conservative estimate of the required number of adults.

An estimate of the adult density is also necessary to calculate the volume requirements of the adult space. The data obtained from the mass balance experiments and the landfill experiments are plotted in Figure 33.

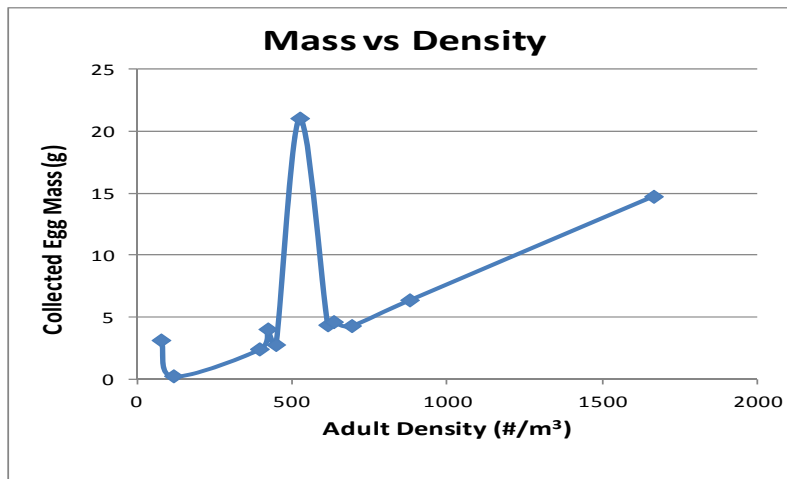


Figure 33 - Adult Density vs. Collected Egg Mass

With the exception of point (526, 21) the graph appears linear, suggesting that higher adult densities could be possible and could result in higher laid egg yields. This relationship is expected to hold up until some critical value after which overcrowding would be expected to reduce laid egg masses. The results from Figure 33 suggest that the optimal density was not achieved during these experiments and as such the highest observed density was used in calculations (1666 adults / m³) (Eqn. 18).

$$\text{Eqn. (18) - Req. Volume for Adult Space for 1 Cell (RV) (m}^3\text{)} = \frac{RA}{AD}$$

Once the required volume of the adult space is known an estimate of the required area can be obtained. For the purposes of this design a height of 4 meters was assumed for the adult space (ASH): because other heights may be advantageous, this input is

adjustable in the design spreadsheet. The required area for one cell is calculated from Eqn. 19.

$$\text{Eqn. (19) - Req. Area for Adult Space for 1 Cell (m}^2\text{)} = \frac{RV}{ASH}$$

The required hatchery area was then calculated; this calculation is dependent upon number of eggs (or egg clutches) that can fit into the egg laying structures. During this research, the females laid their eggs in cartridges with channels whose area measured 15 mm². The depth of these cartridges was kept constant throughout the research at 25.4 mm. This length was chosen because it allowed the females to insert their ovipositor into the channel mimicking the crevices where females prefer to deposit eggs.

Because this depth may not be the optimum channel depth, only the exposed surface area was considered in the design equations. Based on experimental observations, it was assumed that 2 clutches or 800 eggs could fit in the surface area of an egg laying channel. If deeper channels are used, the number of eggs (or egg clutches) that could fit in the channel would also change. Eqn. 20 shows the calculation.

$$\text{Eqn. (20) - Hatchery Area for 1 Cell (m}^2\text{)} = \frac{RE}{\frac{\# \text{ of eggs}}{\text{area of egg laying crevice m}^2}}$$

The area requirement for a system can now be determined by summing the area requirements for a cell and its corresponding adult space as shown in Eqn. 21.

$$\text{Eqn. (21) - System Area Requirement (SAR) (m}^2\text{)} = \text{Adult Space Area} + \text{Cell Area}$$

The number of systems that can fit into a facility can now be determined as shown in Eqn. 22.

$$\text{Eqn. (22) - \# of Systems in Building Area (\#)} = \frac{\text{Building Area}}{SAR}$$

The facility's waste handling capacity was calculated from the ARPW, the number of systems that the facility can house, and the DMMPW (Eqn. 23).

Eqn. (23) – Facility Waste Capacity (FC) (ton/cycle time) =

$$\frac{\text{Reactor Cell Size} * \text{Number of Systems in Building Area}}{\text{ARPW}}$$

These values were then used to estimate the diversion percentage of the facility on a yearly basis (Eqn. 24).

$$\text{Eqn. (24) – Tonnes Diverted (ton)} = \frac{365}{\text{Cycle Time}} * FC$$

At this point, the facility's maggot output for a given cycle time could be estimated. This value is equal to the number of cells that can be housed in the facility (Eqn. 25).

Eqn. (25) – Facility Maggot Output (FMO) (ton of mag) = System # in Building Area

To determine the actual parameters in the adult space for the facility, Equations 14 to 20 were multiplied by the result obtained from Equation 22. The proceeding formulas assume this operation has occurred.

An estimate of harvest capacity for the facility can be calculated after the number of prepupa needed to sustain the colony is calculated (Eqn. 26).

$$\text{Eqn. (26) – Harvest Capacity (\%)} = \frac{(MP-RA)}{MP} * 100$$

The facility's maggot number output can be determined using the product of Eqns. 14 and 22.

5.4.2 Design Case 2 – No Existing Building

In the case where a building does not exist and a new facility must be constructed, the spreadsheet example assumes that all of the daily waste will be collected for processing once per cycle length but this assumption can be changed. The calculations begin by

using the application flux to determine the size of the building required to process the desired quantity of waste (Eqn. 27).

$$\text{Eqn. (27) - Building Area (m}^2\text{)} = \frac{1000 \text{ kg/t}}{AF} * \text{Available Waste for Processing}$$

All subsequent calculations are the same as those in the case where a building does exist and begin with Equation 11.

5.5 Error Propagation

The error from sampled data was carried throughout the calculations to illustrate the possible range of each parameter. The approach used depended on the arithmetic operation and the equations used are summarized as follows:

For addition and subtraction using standard deviations

$$\Delta z = \sqrt{(\Delta x)^2 + (\Delta y)^2 + \dots}$$

Where Δz is the standard deviation of the result and Δx and Δy are the standard deviations of the addition or subtraction terms.

For multiplication and division terms using standard deviations

$$\frac{\Delta z}{z} = \sqrt{\left(\frac{\Delta x}{x}\right)^2 + \left(\frac{\Delta y}{y}\right)^2 + \dots}$$

Where Δz is the standard deviation of the result and Δx and Δy are the standard deviations of the multiplication or division terms; z is the either the product or quotient and x, y are the multiplication or division terms.

Sometimes a series of averages with standard deviations were used to calculate an intermediate value or the final design parameter. When this occurred the following formulas were used to obtain the final average and standard deviation.

$$Final\ Average = \frac{Avg\ 1 + Avg\ 2 + Avg\ 3 + \dots + Avg\ n}{n}$$

$$Final\ Stdev = \sqrt{\frac{std1^2 + std2^2 + std3^2 + \dots + stdn^2}{n}}$$

The use of these formulas allowed for sampling errors to be propagated throughout all calculations.

5.6 Data Variability

The calculated cDCRM value used for design purposes illustrates a high degree of variability. Although part of this variability can be explained by the feeding behaviour of the maggots within the RS – sometimes maggots leave the food source or they die, they eat more when they are larger – the majority of the variability for the design cDCRM is suspected to originate from the difference in maggot numbers obtained from each cycle.

As previously discussed the number of maggots can change significantly from one cycle to the next (the reasons for these changes were discussed in previous sections) and because the maggot number is the basis for the calculation of the cDCRM which in turn is used to calculate other variables, the variability is carried forward to other design parameters. Because the example case is only meant to show the sequence of design steps to size a facility these variations are omitted in the main text but they are presented in Appendix H.

Another potential contributor is the way area was measured; the food pile was generally not a perfect polygon but an irregular shaped mass that required an estimate of the area. This estimation likely contributed to the observed variability within the maggot number estimates.

Chapter 6 – Life Cycle Inventory and Cost Assessment

6.0 Life Cycle Inventory and Cost Assessment

In this research, a facility to propagate the species *Hermetia illucens* in northern climates was designed, constructed and operated for two years at the Essex Windsor Solid Waste Authority's landfill. During this operation natural gas, electricity, water and labour inputs were used to keep the BSF colony alive in the summer and winter months. The use of BSF to process organic wastes possesses advantages over traditional waste management approaches to organic waste (such as composting) but an overall analysis of its sustainability and impacts has yet to be undertaken. To set up the groundwork for a sustainability assessment of an engineered system to propagate the BSF species a life cycle inventory (LCI) was conducted. Although the conditions established in this research are unique to the testing undertaken, this chapter presents an example design case and an overview of the potential operating costs using the research undertaken in order to demonstrate how a life cycle evaluation could be conceptualized. The results and conclusions drawn from this analysis are therefore only applicable to the prototype conditions.

6.1 Scope

The scope of this inventory was limited to the operation of the test facility under the research conditions. This included the:

- Transfer of waste from the generator;
- Feed preparation prior to feeding;
- Energy and water inputs required by the system to perpetuate the species' life cycle;
- Removal and disposal of wastes; and
- Maintenance of the facility.

The construction phase of the facility was omitted because different materials and their duration of use varied significantly as design changes were implemented throughout the

system's operation. Decommissioning issues were also omitted from the LCI as these were specific to the research requirements as opposed to operational requirements.

6.2 Prediction of Potential Impacts

Although the research was conducted at an operating landfill, an actual waste processing facility using BSF does not need to be located at a landfill. The environmental impacts from an operating BSF facility would be similar to those of landfill or composting facility. The following issues would be relevant during the operation of a BSF facility:

- Noise – due to vehicles and possibly machinery used in daily operations;
- Odours – if properly managed odours should be minimized. However, the sensitivity to odours and their acceptable limits varies by individuals so complaints would be expected;
- Surface water and groundwater impacts – the facility is not expected to generate wastewater in appreciable quantities. However, if wastewater is generated it could cause unacceptable discharges to surface and sub-surface waters if not properly managed;
- Pests – although the BSF themselves are not considered pests or disease vectors, BSF are, or can be, a food source to pests and / or disease vectors; and
- Solid wastes – the BSF process produces a waste residue that has value as a fertilizer and soil additive but unless there is a demand for such a material, it may require disposal or storage. Storage outdoors could lead to issues affecting surface and sub-surface waters and possibly odour complaints.

In choosing a location for a facility, the area's sensitivity to the preceding, and other location relevant issues, should be evaluated.

6.3 Resource Use

The predominant resources used by the research facility were electricity, water and to some extent, manual labour. Manual labour was excluded in the LCI because it is common to many waste management options, and the activities undertaken in this research project are specific to the needs of demonstrating the proof-of-concept. In addition to these resources, natural gas was also consumed during the winter months to heat the facility. No other resource inputs were required during the facility's operation in significant quantities.

The consumption pattern of resources varied during the winter and summer weather seasons. For the purposes of this analysis, the winter season began on the first day when the furnace was turned on (typically mid-October) and ended when it was turned off (typically mid-May). The main differences between these two operational seasons were as follows:

- During the winter period natural gas was used to heat the facility and the use of supplemental lighting was necessary; and
- During the summer period larger amounts of water were required and two fans were operated to help cool the facility.

Transportation of the waste to the processing location did not change throughout the facility's operation. Waste produced from operations was disposed at the EWSWA's landfill for the duration of the study.

6.4 Life Cycle Inventory

The facility's operations were organized into processes for analysis. The first process considered was transporting the restaurant waste to the facility. In this case the generation source was a restaurant located approximately 36 km from the facility. This distance was travelled three times per week. The round trip distance was used to estimate fuel requirements for the vehicle's operation.

The fuel consumption required to transport the facility's solid wastes for disposal was low because the final disposal site was located on the same property and the facility's waste residues were not disposed continuously, but rather only once per cycle, on average once every 36 days. The only other routine use for the vehicle was the transportation of water from the source to the facility; this operation was done once every two weeks for the duration of the research.

The first process inside the facility was defined as the preparation phase in which the waste food was ground up and stored for future use. A 2.2 kW grinder, water and manual labour were utilized for this task and its associated cleaning operations. After this stage was complete the actual waste processing and life cycle propagation stages began.

The BSF propagation system required various machinery to maintain its operation: these included pumps, solenoids, lighting systems and fans. All of these systems were set to operate in periodic fashion that was controlled by timers. The only machine that operated independently of a timer was the main water delivery pump; the pump's on / off cycles was controlled by a pressure switch.

The main water pump's operation was connected to the operation of dependent devices; for example, if the misting pump operated the main pump would also operate for a given amount of time. This operational time of the main pump varied depending on the device being used.

In an attempt to quantify the main pump's operational times, the dependent devices, (the mister, grinder, collection system etc.) were set to operate continuously for five minutes. The main pump's operation was then timed so that a time ratio of the dependent device's run time to the main pump's run time could be estimated. Once this ratio was known the amount of electricity used by the main pump could be estimated for each minute of the dependent device's operation.

The flow rate of every device was also obtained to determine how much water was used for a given task. When this was not possible, the water usage was estimated. All water consumption values were normalized to a volume per day basis.

Electrical power consumption was either obtained directly from specifications printed on the device or calculated given the supplied voltage, current ratings and time of operation. All devices operated on timers or continuously. Electricity consumption was normalized to kWh per day.

The use of natural gas was tracked via a meter located outside the outer greenhouse. The readings were collected on a monthly or bi-monthly period. The heating system was the only use of natural gas required by the facility's operation.

The following subsystems list describes the use of required devices that were necessary to maintain the life cycle of the BSF during this research:

- Outer greenhouse – during the winter no systems are used. In the summer season, the outer greenhouse fan and the ventilation louvers were required to maintain operational temperatures;
- Inner greenhouse – during the winter, the furnace maintained the temperature. In the summer season the inner greenhouse fan operated in conjunction with the misting system to cool the facility. A recirculation fan and four humidifiers operated in both seasons. The main water pump provided pressure for the water supply. A grinder was used to process waste prior to feeding;
- Reactor space – operations did not change in either season. The only direct use of energy was a misting system connected to a solenoid that was controlled by a timer;
- Exit ramp – no energy was consumed by this subsystem;
- Water collection system – an electric pump was used to circulate water through the collection tubes under the control of a timer;
- Water / maggot separator – no energy was consumed by this subsystem;

- Pupation chamber - no energy was consumed by this subsystem;
- Adult space – operations in winter required a lighting system that included a cooling fan to supplement sunlight. Water for the adults was provided by the same mister that cooled the inner greenhouse; and
- The hatchery – operations did not change in the winter or summer seasons. Humidification is powered by two fogging units. Hot air was provided by the fan that cooled the lighting system in the adult space.

The use of each resource by each device was calculated and tabulated to obtain a usage value on a per day basis. Because resource use changed between summer and winter, separate values were calculated for each season. The estimates provided were based on operational times that were sometimes specific to each device. A list of these assumptions can viewed in Appendix J. Because the timers were assumed to operate in a consistent fashion, standard deviations for each resource used were assumed to be negligible.

The following tables outline water and electricity usage during the winter and summer periods for the various systems. The complete tables can be viewed in Appendix K.

Table 17 - LCI Winter Resource Consumption

Water and Electricity Consumption - Winter Period					
Water Usage	Q (L/min)	V (L/d)			
Mister Adult Room (4 nozzles)	0.304	0.5			
Mister Reactor (5 nozzles)	0.142	1.4			
Humidifier Hatchery	0.003	4.3			
Humidifier 1	0.005	7.2			
Humidifier 2	0.005	7.2			
Humidifier 3	0.0092	13.2			
Humidifier 4	0.032	46.1			
Grinding	0.00198	2.9			
Flooding	0.001311	1.9			
Water Collection	0.00275	4.0			
Cleaning Operations	0.001884	2.7			
Total (L/d)		91.3			
Electricity Usage	Operation Time (min/d)	Volts	Amps	Wattage	kWh per day
Humidifier 1	1440	120	0.5	60.0	1.4
Humidifier 2	1440	120	0.5	60.0	1.4
Humidifier 3	1440	120	1.0	120.0	2.9
Humidifier 4	1440	120	0.6	72.0	1.7
Recircfan (on vent btwn main room and adult room)	1440	120	0.8	90.0	2.2
Water Collection System Pump	32	120	1.1	132.0	0.1
<i>Water Master Pump</i>					
<i>--Grinder</i>	0.7				
<i>--Reactor Misting (directly powered by main pump)</i>	10.0				
<i>--Adult Chamber Water</i>	0.8				
<i>--Random Hose Use</i>	0.3				
<i>Master Pump Total</i>	11.8	120	11.4	1368	0.269
Light	720.0	120.0	8.3	1000.0	12.0
Light Fan	720.0	120.0	1.0	116.4	1.4
Mister Pump	1.5	120.0	7.2	864.0	0.0
Foggers	1440.0	24.0	0.2	4.8	0.1
Grinder	1.4	208.0	7.0	1456.0	0.0
Furnace Exhaust Fan	360.0	120.0	1.8	216.0	1.3
Furnace Blower Motor	360.0	120.0	8.2	984.0	5.9
				Total kWh per day	30.8

Table 18 - LCI Summer Resource Consumption

Water and Electricity Consumption - Summer Period					
Water Usage	Q (L/min)	V (L/d)			
Mister Adult Room and GH Cooling (10 nozzles)	0.76	35.3			
Mister Reactor (5 nozzles)	0.142	1.4			
Humidifier Hatchery	0.003	4.3			
Humidifier 1	0.005	7.2			
Humidifier 2	0.005	7.2			
Humidifier 3	0.0092	13.2			
Humidifier 4	0.032	46.1			
Grinding	0.00198	2.9			
Flooding	0.001311	1.9			
Water Collection	0.00275	4.0			
Cleaning Operations	0.001884	2.7			
Total (L/d)		126.2			
Electricity Usage	Operation Time (min/d)	Volts	Amps	Wattage	kWh per day
Outer Greenhouse Fan	1200	120	13.4	1608	32.2
Inner Greenhouse Fan	1440	120	3.5	420	10.1
Ventilation Louvres	1440	120	1.5	180	4.3
Humidifier 1	1440	120	0.5	60	1.4
Humidifier 2	1440	120	0.5	60	1.4
Humidifier 3	1440	120	1.0	120	2.9
Humidifier 4	1440	120	0.6	72	1.7
Recircfan (on vent btwn main room and adult room)	1440	120	0.8	90	2.2
Water Collection System Pump	32	120	1.1	132	0.070
<i>Water Master Pump</i>					
<i>--Grinder</i>	0.7				
<i>--Reactor Mister</i>	10.0				
<i>--Adult Chamber Water and GH cooling water</i>	23.3				
<i>--Random Hose Use</i>	0.3				
<i>Master Pump Total</i>	34.3	120	11.4	1368	0.8
Light	0.0	120	8.3	1000.0	0.0
Mister Pump	46.5	120	7.2	864.0	0.7
Foggers	1440.0	24	0.2	4.8	0.1
Grinder	1.4	208	7.0	1456.0	0.035
				Total kWh per day	57.9

The entire facility process can be viewed in the following flow chart. Inputs to each stage are listed in the green boxes and wastes are listed in the red boxes. The blue arrows show the progression from stage to the next. The following list explains the abbreviations:

- MP – manpower or labour inputs;
- e⁻ - electricity input; and
- WW – wastewater.

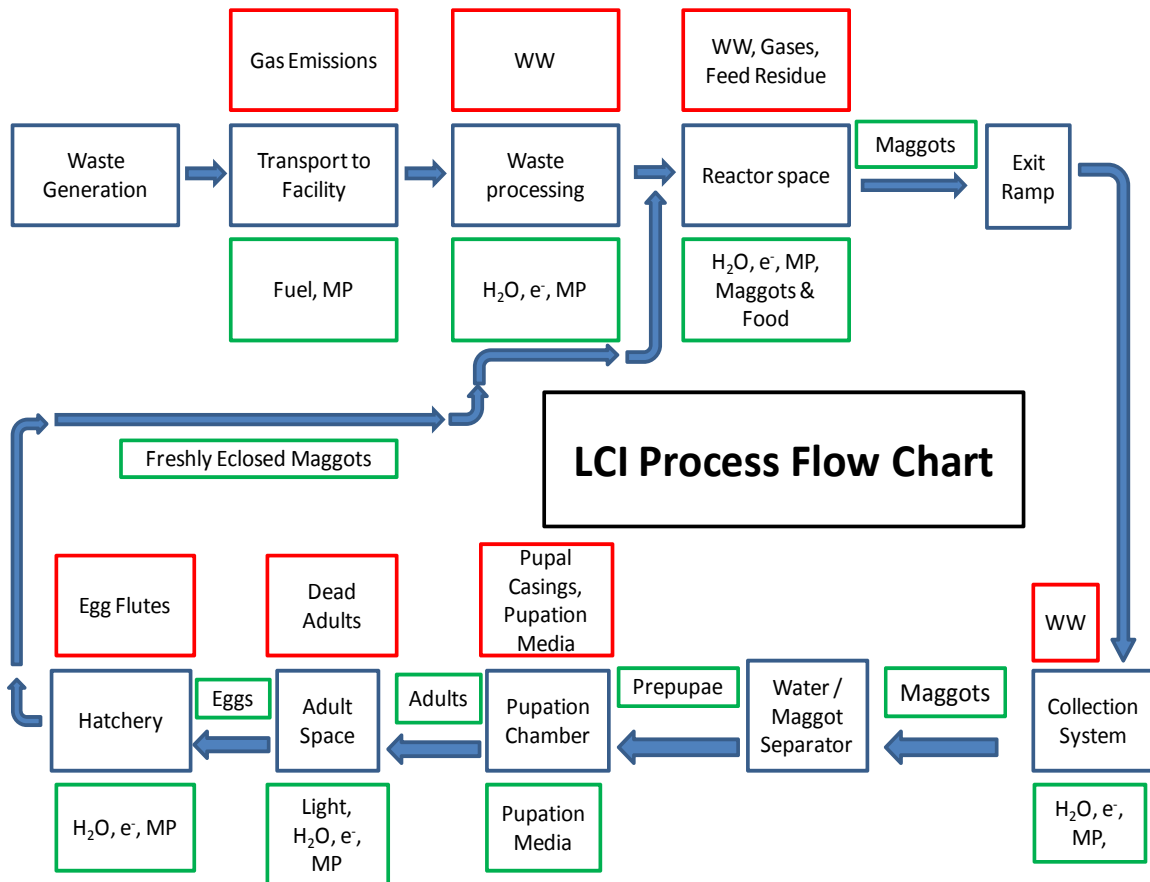


Figure 34 - LCI Process Material Flows

The quantity and type of gases emitted during the waste processing stage were not studied. CO₂ is emitted by the respiration of the maggots. Other volatiles are most likely present from the bacterial decomposition and maggot reduction of the waste but assessing these gases was outside the scope of this research. However, based on the observed odours, ammonia is likely present as a by-product of protein consumption.

6.5 Routine Maintenance

There were two types of maintenance required by the facility; the first was the repair or replacement of machinery. These instances were not tracked because they varied in the

amount of time, resources and materials required to rectify the situation. The second type was considered routine operational maintenance.

Wastewater generation came from routine maintenance operations only; added water to the RS either left the system as water vapour, in the waste residue or via the drain. Any water leaving via the drain was collected and reused in the RS. These amounts were insignificant. The sources of wastewater are presented in Table 19 and because the maintenance processes were not considered seasonal, neither was the wastewater generation.

Table 19 - Wastewater Generation

Wastewater Generation (Not Seasonal)	Q (L/min)	V (L/d)
Flooding	0.001311	1.9
Grinder Cleaning	0.00198	2.9
Water Collection System Cleaning	0.00275	4.0
Total (L/d)		8.7

From Table 19, the largest contributor to the wastewater generation is the maintenance surrounding the collection system. The water used as the working fluid in the water collection system also required replacement every three weeks during normal operations. Although some of the water contained soluble wastes, the major reason for replacing it was the buildup of solids that could impede the efficient operation of the pump. In a full size facility, a solids filtration system could extend the working life of the fluid and reduce the amount of wastewater generated. After grinding operations the grinder required cleaning using water that was eventually discarded as waste.

The flooding process was done every six months to force any hidden maggots out of the pea gravel during the trickling filter operational phase and to help clean the void spaces between the pea gravel. The need for RS flooding was eliminated when the trickling filter set up was abandoned but it is included in the analysis because of the significant amount of water used.

In both circumstances the water was discarded into the wetland system of the outer greenhouse. Prior to this research, the outer greenhouse was used to treat leachate from the landfill with the aid of plants. When the BSF research first began, the plants in the polishing stage of the artificial wetland were in poor condition and growth was scarce.

After approximately four months of operation the plants' condition improved and their numbers increased. All other sources of water except infiltration were absent suggesting that the wastewater contained nutrients that the plants were able to use for growth and could function as a fertilizer. Nutrient testing of the grinder's cleaning water and the collection system's waste water as well as the wetland's effluent was not conducted to determine the extent of nutrient uptake by the plants. As stated previously however, this process wastewater could conceivably be used for agricultural purposes.

The last form of maintenance was disposing of the pupation medium. The medium replacement time varied depending on the amount of infestation of undesirable species present, typically once every six to seven months. This task was done after emergence of the adults so that all the materials could be discarded at once. This maintenance is most likely avoidable in preliminary systems because there is no reason to remove the pupation medium if infestations are not present. No other forms of maintenance were required.

6.6 LCI Metrics

In total twelve cycles were run during the course of this research each producing a differing amount of maggots. These data are listed in Table 20.

Table 20 - Cycle Lengths and Maggot Number

Reactor Data				
Cycle	Start Date	End Date	Length (d)	Estimated Max Mag #
1	13/01/10	19/02/10	38	23648
2	26/02/10	01/04/10	35	101209
3	02/04/10	28/04/10	27	34749
4	30/04/10	21/06/10	53	331236
5	23/06/10	12/07/10	20	13314
6	23/08/10	20/09/10	29	10680
7	22/09/10	19/11/10	59	111544
8	22/11/10	31/01/11	71	184230
1	18/02/11	28/03/11	39	23405
2	13/04/11	17/05/11	37	36454
3	24/05/11	03/06/11	11	6254
4	06/07/11	20/07/11	15	5828

As a precursor to future life cycle assessments, the resource consumption was normalized. These could serve as starting points for more elaborate studies. Given the cycle length, the maximum number of maggots attained in a cycle and the per day resource use during each cycle, normalized data for each cycle and resource were calculated. The results in Table 21 show the continuous (C) and batch (B) operational cycles. These calculations are shown in Appendix L.

Table 21 - Resource Consumption per Maggot

Cycle #	Start	End	Water Use (L/Mag)	Elec. Use (kWh/Mag)	Natural Gas (m ³ /Mag)	Trans. Fuel (L/Mag)	WW (L/Mag)
1C	13/01/2010	19/02/2010	0.147	0.049	0.053	0.008	0.014
2C	26/02/2010	01/04/2010	0.032	0.011	0.021	0.002	0.003
3C	02/04/2010	28/04/2010	0.071	0.024	0.025	0.004	0.007
4C	30/04/2010	21/06/2010	0.020	0.009	0.000	0.001	0.001
5C	23/06/2010	12/07/2010	0.190	0.087	0.000	0.008	0.013
6C	23/08/2010	20/09/2010	0.343	0.157	0.000	0.014	0.024
7C	22/09/2010	19/11/2010	0.048	0.016	0.018	0.003	0.005
8C	22/11/2010	31/01/2011	0.035	0.012	0.010	0.002	0.003
1B	18/02/2011	28/03/2011	0.152	0.051	0.037	0.009	0.014
2B	13/04/2011	17/05/2011	0.093	0.031	0.000	0.005	0.009
3B	24/05/2011	03/06/2011	0.222	0.102	0.000	0.009	0.015
4B	06/07/2011	20/07/2011	0.325	0.149	0.000	0.013	0.022

The cycles were then ranked by the lowest water and electricity consumption and the results are shown in Table 22.

Table 22 - Ranked Resource Consumption per Maggot

Cycle #	Start	End	Water Use (L/Mag)	Elec. Use (kWh/Mag)	Natural Gas (m³/Mag)	Trans. Fuel (L/Mag)	WW (L/Mag)
4C	30/04/2010	21/06/2010	0.020	0.009	0.000	0.001	0.001
2C	26/02/2010	01/04/2010	0.032	0.011	0.021	0.002	0.003
8C	22/11/2010	31/01/2011	0.035	0.012	0.010	0.002	0.003
7C	22/09/2010	19/11/2010	0.048	0.016	0.018	0.003	0.005
3C	02/04/2010	28/04/2010	0.071	0.024	0.025	0.004	0.007
2B	13/04/2011	17/05/2011	0.093	0.031	0.000	0.005	0.009
1C	13/01/2010	19/02/2010	0.147	0.049	0.053	0.008	0.014
1B	18/02/2011	28/03/2011	0.152	0.051	0.037	0.009	0.014
5C	23/06/2010	12/07/2010	0.190	0.087	0.000	0.008	0.013
3B	24/05/2011	03/06/2011	0.222	0.102	0.000	0.009	0.015
4B	06/07/2011	20/07/2011	0.325	0.149	0.000	0.013	0.022
6C	23/08/2010	20/09/2010	0.343	0.157	0.000	0.014	0.024

The results of the ranking can be explained by the amount of maggots produced by each cycle. Cycles two, four and eight produced the greatest amount of maggots for the amount resources used. Cycle four is the only cycle in the top five that occurred in the summer: the other cycles occurred in the winter season and therefore also required the use of natural gas for heating. This suggests that, because of the greenhouse setup, it was easier to maintain habitable conditions in the winter than in the summer time. A greenhouse setup that is operationally sound is therefore critical to the success of any overall BSF facility, and will probably better serve the needs of the BSF's rather extensive intervention technologies (e.g., heating or cooling).

What is missing from this LCI is a characterization of the gases released during this process. The composition of these gases and therefore the greenhouse gas contribution of this process are not known.

Direct comparison of the BSF process to a landfilling operation is difficult. Both facilities are designed to manage incoming waste streams but a landfill is considered final disposal because nothing comes out of it with the exception of potential groundwater

pollutants and methane gas. Although methane gas can be collected and used as a fuel, the end result is CO₂ emissions.

The BSF process is designed to be cyclical in nature keeping nutrients and materials as a part of the food chain.

6.7 Example Design, EWSWA Projected Waste Tonnage 2012

In order to determine the process's commercial viability a conceptual cost analysis of the operations was completed. The scenario describes the use of the large greenhouse structure at the EWSWA.

In this case study the organic portion of municipal solid waste (MSW) was assumed to be equal in nutritional content as the restaurant waste used in the experiments.

Although this is most likely not the case, the emphasis of the case study is to show *how the design process* would be applied to a waste management scenario. It is recommended that small waste consumption test studies should be conducted with the desired food source to determine the waste loading rate for a given food source.

The content of municipal solid waste is also a concern because it can contain materials and substances that could kill the maggots or could be bio-amplified in their fat reserves. Source separation of the MSW will most likely be necessary and costs associated with this process have been omitted. In addition, prepupae generated by the facility will need to be preserved for transport – possibly freeze dried. Costs associated this process have also been omitted.

Transportation costs have been omitted because waste must be transported from the generation sites to a disposal site regardless of the final disposal method but these savings would likely be offset by the necessity to sort out the organic portion of the waste stream. Construction or retrofitting costs and capital expenditures are also unknown and have therefore been omitted. It was assumed that if the facility can

generate revenue after its operating expenses, then construction and capital costs can be recuperated.

For illustrative purposes, the unit cost of water, electricity and natural gas, were normalized to a “cost per unit area” to determine the operational costs under the research conditions: these costs were then used to estimate the operational costs of a larger building. The unit costs are summarized in Table 23. It was assumed that the heat transfer rate of the outer greenhouse and the inner greenhouse was the same on a unit area basis to facilitate analysis. Cost calculations are available in Appendix L.

Table 23 - Resource Costs per Unit Area of Facility

Resource Costs (\$/m²)	
Water	0.03
Electricity	0.48
Natural Gas	3.72

When used as a nutrition source for the production of other animal species the value of the produced maggots ranges between \$1500 to \$2000 USD per ton³. The middle range of this value, \$1750, was used for a cursory monetary analysis of the process using the research scenario at the EWSWA. Other potential revenue sources from the operation such as the waste residue and the left over chitin were not considered, only the potential value of the maggots.

The value of the maggots was also restricted to their use as a protein source for other forms of livestock or aquaculture. Harvesting the maggots as a source for industrial chemicals or their precursors was not considered.

The expected tonnage of waste to the EWSWA regional landfill in 2012 was used as an example design case. The expected tonnage value was obtained from the EWSWA budget projections for 2012. The example spreadsheet follows and results are shown in

³http://www.organicvaluerecovery.com/our_process/our_process.htm

Tables 24 to 28. The cycle time used was the average of the observed cycle times throughout the research, 36 days. When calculating the hatchery area requirements, it was assumed that 2 egg clutches or approximately 800 eggs would fit into the egg cartridge channels with dimensions of 15 mm by 15 mm by 25.4 mm deep. This value was based on observations obtained during the course of the research. Values in red are customizable to reflect changes in real world applications.

Table 24 - Case Inputs

Case Inputs	Values
<u>Expected Tonnage EWSWA 2012</u>	
(ton/year)	170000
(ton/day)	466
Landfill Tipping Fee (\$/ton)	\$ 58.00
<u>Waste Characteristics</u>	
Moisture Content of Waste (decimal)	0.6
Organic Fraction of Waste Stream (decimal)	0.4

Table 25 - Resource Usage

Resource Usage	
Usage in 36 days	Parameter
Average Water Use per Cycle (L)	3828
Average Electricity Use per Cycle (kWh)	1522
Average Natural Gas Use Per Cycle (m ³)	626
Costs	
Water Cost (\$/L)	0.0003
Electricity Use (\$/kWh)	0.11
Natural Gas (\$/m ³)	0.2
Average Costs per Resource in 36 days (\$)	
Water	1
Electricity	167
Natural Gas	125
Research Resource Costs per Unit Area per 36 days (\$/m²)	
Water	0.03
Electricity	0.48
Natural Gas	3.72

Table 26 - Physical Properties of Maggots

Waste Conversion Data	Parameter
Average Cycle Length (d)	36
Average Waste Cycle Reduction (%)	44
Average Dry Matter Consumption Rate (g/mag/d)	0.0278
Waste Consumption (g/mag/36 days)	1.00
# of Maggots Required to Consume 1 Ton of Waste in 36 days (mag/ton)	997722
Dry Waste Application Flux	
(g/d/cm ²)	0.195
(kg/d/m ²) (Eqn 10)	1.95
Physical Maggot Measurements	
Number of maggots per unit area (mag/cm ²)	7
Maggot Survival Rate (dec)	0.8
Moisture Content of Prepupae (dec)	0.08
Number of maggots per unit area (mag/m ²)	70000
Average Cross Sectional Area of maggots (cm ²)	0.13
Average Volume of maggots (cm ³)	0.25

Table 27 - Scenario 1 Existing Building

If Building Exists	Parameter
<u><i>Reactor Dimensions</i></u>	
Building Area (m ²)	348
Reactor Area Required to Process One Ton of Dry Waste (m ²) (Eqn 11)	14
Dry Mass of Maggots Produced From 1 Ton of Dry Waste (kg) (Eqn 12)	113
Cell Size - Reactor Area Required to Produce One Dry Ton of Maggots (m ²) (Eqn 13)	126
Number of Maggots in One Dry Ton of Maggots (Eqn 14)	7,072,191
System Area Requirement (1 Reactor Cell & Adult Space for 1 Cell) (m ²) (Eqn 21)	162
Number of Systems That Can Fit in Building (Eqn 22)	2.2
Facility Waste Capacity (ton/36 days) (Eqn 23)	19
Organic Waste Diverted (ton/year) (Eqn 24)	193
Facility Maggot Output (ton/36 days) (Eqn 25)	2.2
Dry Organic Waste Diverted (%)	0.71
Egg Survival Rate (dec)	0.6
Average Number of Eggs per Clutch (#)	400
Percentage of Mating Adults (dec)	0.5
Percentage of Emergence (dec)	0.5
# of Egg Clutches Per Egg Laying Crevice	800
Egg Laying Crevice Area (m ²)	0.000015
Adult Space Height (m)	4
Adult Density (#/m ³)	1666
<u><i>Adult Room Size for 1 Cell</i></u>	
Number of Prepupae from 1 Cell (#) (Eqn 14)	7,072,191
Number of Eggs Required from to Sustain 1 Cell (#) (Eqn 15)	11,786,986
Equivalent Number of Clutches 1 Cell (#) (Eqn 16a)	29,467
Number of Mating Pairs 1 Cell (#) (Eqn 16b)	29,467
Number of Mating Adults 1 Cell (#) (Eqn 16c)	58,935
Required Number of Adults 1 Cell (#) (Eqn 17)	235,740
Volume of Adult Space for 1 Cell (m ³) (Eqn 18)	142
Floor Area of Adult Space 1 Cell (m ²) (Eqn 19)	35
Hatchery Area for 1 Cell (located inside adult space area) (m ²) (Eqn 20)	0.22
<u><i>Adult Room Size for Facility</i></u>	
Prepupae Produced by Facility (#)	15,223,667
Number of Eggs Required to Sustain Facility (#)	25,372,779
Equivalent Number of Clutches for Facility (#)	63,432
Number of Mating Pairs for Facility (#)	63,432
Number of Mating Adults for Facility (#)	126,864
Required Number of Adults for Facility (#)	507,456
Volume of Adult Space for Facility (m ³)	305
Floor Area of Adult Space for Facility (m ²)	76
Hatchery Area for Facility (located inside adult space area) (m ²)	0.48
Facility Harvest Capacity (%) (Eqn 26)	97
Number of Prepupae Available for Harvest (#)	14,716,212
Prepupae Produced by Facility for Harvest (ton)	2.1

It is noteworthy to mention that the area calculations only include the space requirements for the reactor vessel, the adult space and the hatchery. Additional considerations must also be made for equipment, personnel access, machinery and material handling space.

In the EWSWA's case, the existing outer greenhouse, with an area of approximately 348 m², was conceptually used as a building to house the process for an incoming stream of organic waste. Using the resource consumption rates under the research conditions, the greenhouse's waste processing capacity is approximately 19 tons every thirty-six days and it will generate approximately 2.2 tons of maggots. The costs for water, electricity and natural gas were scaled to reflect the size of the greenhouse present at the EWSWA landfill site and are presented in Table 28.

Table 28 - Scenario 1 Existing Building Costs

Resource Costs for an Existing Building Size	Cost
Water (\$)	\$ 11.89
Electricity (\$)	\$ 167.45
Natural Gas (\$)	\$ 1,296.06
Total Operational Costs	\$ 1,475.41
Value of Maggots per Ton	\$ 1,750.00
Revenue From Maggots	\$ 3,641.50
Diverted Waste Credit	\$ 1,106.24
Net Value without Diverted Waste Credit	\$ 2,166.09
Net Value with Diverted Waste Credit	\$ 3,272.33

It can be seen that under the conceptual research conditions, the facility is making approximately \$2,166 every thirty-six days of operation and it is diverting approximately 193 tons per year of waste or roughly 0.71% of the yearly total waste input to the landfill. If a credit is assigned to the facility for each ton of waste diverted from the landfill the net value increases to \$3,272. Although this seems like a favourable scenario, it should be remembered that other costs would be present. Also, improvements to the facility can be made to further improve the facility's efficiency.

When compared to the current waste processing option of landfilling, which charges a tipping fee of \$58 per tonne, the use of the BSF facility may be commercially viable under current operational parameters. The use of BSF as a treatment option could be viable and suitable. Improvements should be made to the process: these improvements include efficient energy usage via operation in a building designed or retrofitted for energy efficiency and increasing the amount of waste that can be processed per unit area.

6.7.1 Suggested Facility Improvements

There are two major improvements that can be made:

- 1.) The application flux of the waste must be improved. Under the research conditions the temperature and humidity variations most likely prevented optimal waste consumption rates. An improved application flux, such as those achieved under more controlled conditions by Diener et. al. (2009), 3 to 5 kg/d/m², would make the reactor vessel smaller so that less space would be required to process waste. The stabilization of abiotic conditions through the use of adequate heating, cooling and humidification should increase the application flux values to those observed by Diener et. al. (2009).
- 2.) The physical distribution of maggots in the reactor vessel should be improved. During the research only one layer of maggots was observed during active feeding in the food pile. No significant numbers of maggots were observed to feed under this primary layer, which was typically 2.54 to 3.8 cm in depth. This was most likely a consequence of oxygen availability at the surface and the lack of it at greater depths. If aeration could be provided the number of maggots that could “fit” under a given unit area could be increased thereby increasing the system’s consumption rate and the number of maggots produced for a given reactor size. This would in turn increase revenues.

Further research and experimentation is necessary to determine the feasibility of these improvements.

The configuration of the reactor cells is also an important consideration. The area maybe broken up into manageable sizes given space constraints within a particular building but special attention should be paid to redundancy. One unit is not recommended for the entire cell area or the adult space. In order to minimize potential problems from disease or toxicity the required cell area should be divided into sections. The adult space and hatchery area requirements can also be divided into sections. Ideally multiple reactor vessels would supply adults to an adult area as illustrated in Figure 35. Although not shown, the perimeter of the adult space can be increased to allow for maintenance access.

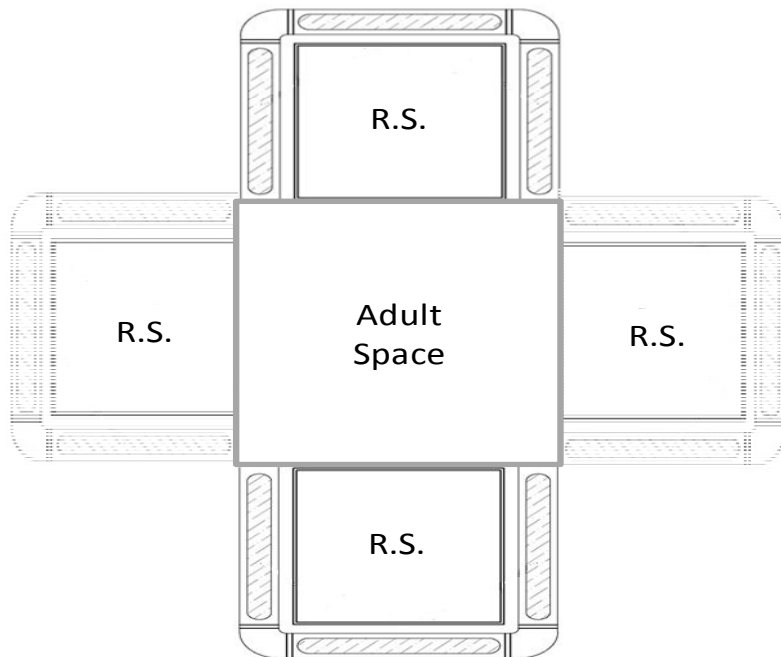


Figure 35 - Proposed Layout for Reactor Vessels & Adult Space

It is expected that modest improvements to the application flux and the physical distribution of maggot density in the reactor space would make the operation more profitable and desirable. The practicality of realizing and applying these improvements

requires further research but data from Diener et. al. (2009) suggest that improvements to the application flux are possible.

6.8 Example Design, ESWWA Projected Waste Tonnage 2012 Using Modified Data

The collected data exhibited a high degree of variability. In an effort to attenuate this variability, some of the collected data was excluded and a new application flux was calculated. No other data was changed and the full results can be viewed in Appendix M. The design process was repeated using equations 2 to 16 to show the decrease in variability.

Data associated with entire cycles were removed according to the following criteria:

- 1.) Cycles that lasted 53 days or longer were excluded. This time length was chosen from the average cycle length of 36 days +/- 17 or one standard deviation. This criterion resulted in excluding cycles 4, 7 and 8 during the continuous operational mode.
- 2.) Cycles 3 and 4 during batch operations were also excluded because the colony was functioning under stressed conditions: these included abnormally dry and hot conditions that were the result of equipment failures.

The results from the calculations are presented in the following tables. Values in red signify customizable parameters.

Table 29 - Comparison of Application Flux

	Case 1 - Entire Data Set		Case 2 - Modified Data Set	
Dry Waste Application Flux	Parameter	Stdev (+/-)	Parameter	Stdev (+/-)
(g/d/cm ²)	0.195	0.2	0.184	0.0
(kg/d/m ²) (Eqn 10)	1.95	2	1.84	0
	Case 1 - Entire Data Set		Case 2 - Modified Data Set	
Physical Maggot Measurements	Parameter	Stdev (+/-)	Parameter	Stdev (+/-)
Number of maggots per unit area (mag/cm ²)	7	0.25	7	0.25
Maggot Survival Rate (dec)	0.8	0.00	0.8	0.00
Moisture Content of Prepupae (dec)	0.08	0.00	0.08	0.00
Number of maggots per unit area (mag/m ²)	70000	2514	70000	2514
Average Cross Sectional Area of maggots (cm ²)	0.13	0.04	0.13	0.04
Average Volume of maggots (cm ³)	0.25	0.09	0.25	0.09

As can be seen in Table 29 the application flux does not change by a significant amount but the standard deviation is much smaller.

Table 30 – Reactor Space Design Comparison

	Case 1 - Entire Data Set		Case 2 - Modified Data Set	
If Building Exists	Parameter	Stdev (+/-)	Parameter	Stdev (+/-)
<i>Reactor Dimensions</i>				
Building Area (m ²)	348	0	348	0
Reactor Area Required to Process One Ton of Dry Waste (m ²) (Eqn 11)	14	13	15	4
Dry Mass of Maggots Produced From 1 Ton of Dry Waste (kg) (Eqn 12)	113	104	120	33
Cell Size - Reactor Area Required to Produce One Dry Ton of Maggots (m ²) (Eqn 13)	126	164	126	49
Number of Maggots in One Dry Ton of Maggots (Eqn 14)	7,072,191	427,938	7,072,191	427,938
System Area Requirement (1 Reactor Cell & Adult Space for 1 Cell) (m ²) (Eqn 21)	162	165	162	54
Number of Systems That Can Fit in Building (Eqn 22)	2.2	2.8	2.2	0.8
Facility Waste Capacity (ton/36 days) (Eqn 23)	19	17	18	5
Organic Waste Diverted (ton/year) (Eqn 24)	193	201	182	61
Facility Maggot Output (ton/36 days) (Eqn 25)	2.2	2.8	2.2	0.8
Dry Organic Waste Diverted (%)	0.71	0.74	0.67	0.22

The reactor space's design is also not significantly affected by the subtle change in the application flux but the design is now bound by more reasonable limits.

Table 31 - Adult Space Design Comparison

	Case 1 - Entire Data Set		Case 2 - Modified Data Set	
<u>Adult Room Parameters</u>	Parameter	Stdev (+/-)	Parameter	Stdev (+/-)
Egg Survival Rate (dec)	0.6	0	0.6	0
Average Number of Eggs per Clutch (#)	400	252	400	252
Percentage of Mating Adults (dec)	0.5	0	0.5	0
Percentage of Emergence (dec)	0.5	0	0.5	0
# of Egg Clutches Per Egg Laying Crevice	800	0	800	0
Egg Laying Crevice Area (m ²)	0.000015	0	0.000015	0
Adult Space Height (m)	4	0	4	0
Adult Density (#/m ³)	1666	0	1666	0
	Case 1 - Entire Data Set		Case 2 - Modified Data Set	
<u>Adult Room Size for 1 Cell</u>	Parameter	Stdev (+/-)	Parameter	Stdev (+/-)
Number of Prepupae from 1 Cell (#) (Eqn 14)	7,072,191	427,938	7,072,191	427,938
Number of Eggs Required from to Sustain 1 Cell (#) (Eqn 15)	11,786,986	713,231	11,786,986	713,231
Equivalent Number of Clutches 1 Cell (#) (Eqn 16a)	29,467	18,658	29,467	18,658
Number of Mating Pairs 1 Cell (#) (Eqn 16b)	29,467	18,658	29,467	18,658
Number of Mating Adults 1 Cell (#) (Eqn 16c)	58,935	37,316	58,935	37,316
Required Number of Adults 1 Cell (#) (Eqn 17)	235,740	149,262	235,740	149,262
Volume of Adult Space for 1 Cell (m ³) (Eqn 18)	142	90	142	90
Floor Area of Adult Space 1 Cell (m ²) (Eqn 19)	35	22	35	22
Hatchery Area for 1 Cell (located inside adult space area) (m ²) (Eqn 20)	0.22	0.01	0.22	0.01
	Case 1 - Entire Data Set		Case 2 - Modified Data Set	
<u>Adult Room Size for Facility</u>	Parameter	Stdev (+/-)	Parameter	Stdev (+/-)
Prepupae Produced by Facility (#)	15,223,667	19,757,700	15,223,667	5,929,300
Number of Eggs Required to Sustain Facility (#)	25,372,779	32,893,690	25,372,779	9,762,174
Equivalent Number of Clutches for Facility (#)	63,432	91,518	63,432	46,997
Number of Mating Pairs for Facility (#)	63,432	91,518	63,432	46,997
Number of Mating Adults for Facility (#)	126,864	183,036	126,864	93,993
Required Number of Adults for Facility (#)	507,456	732,143	507,456	375,973
Volume of Adult Space for Facility (m ³)	305	439	305	226
Floor Area of Adult Space for Facility (m ²)	76	110	76	56
Hatchery Area for Facility (located inside adult space area) (m ²)	0.48	0.617	0.48	0.185
Facility Harvest Capacity (%) (Eqn 26)	97	181	97	54
Number of Prepupae Available for Harvest (#)	14,716,212	19,771,261	14,716,212	5,941,208
Prepupae Produced by Facility for Harvest (ton)	2.1	2.8	2.1	0.8
	Case 1 - Entire Data Set		Case 2 - Modified Data Set	
<u>Resource Costs for an Existing Building Size</u>	Cost		Cost	
Water (\$)	\$ 11.89		\$ 11.89	
Electricity (\$)	\$ 167.45		\$ 167.45	
Natural Gas (\$)	\$ 1,296.06		\$ 1,296.06	
Total Operational Costs	\$ 1,475.41		\$ 1,475.41	
Value of Maggots per Ton	\$ 1,750.00		\$ 1,750.00	
Revenue From Maggots	\$ 3,641.50		\$ 3,641.50	
Diverted Waste Credit	\$ 1,106.24		\$ 1,042.29	
Net Value without Diverted Waste Credit	\$ 2,166.09		\$ 2,166.09	
Net Value with Diverted Waste Credit	\$ 3,272.33		\$ 3,208.38	

The design of the adult space is also affected in a similar fashion as the reactor space; the spread of the data is lower. Based on the comparison carried out in this section the physical design of the system was not significantly affected. Costs are also not affected

significantly. The spread of the data however was affected significantly and these new bounds seem to constrain the design of the subsystems within more reasonable limits.

Chapter 7 – Conclusions, Recommendations and Avenues for Further Research

7.0 Conclusions, Recommendations and Areas for Further Research

In this research, the Black Solider Fly (*Hermetia illucens*) or “BSF” is used as a waste management tool in a similar fashion to vermicomposting. This research also determined that a controlled environment can successfully propagate the species at higher latitudes. The conceptual design of a waste facility that could use BSF as the primary waste processing agent was completed. In addition, the groundwork for a sustainability assessment of the process and a comparison to current waste disposal practices for organic wastes was established.

This research propagated a colony of BSF for two years despite some mechanical problems with equipment. A facility was designed, constructed and revised for two years. During these two years, data from eight continuous mode cycles and four batch cycles was collected. This operation included all life cycle stages of the BSF and proved that the flies can be propagated successfully in northern climates.

This research also established a method and identified necessary parameters to design a waste management facility based on the physical properties of the BSF larva. A waste application rate was used to design the primary reactor space and other required infrastructure.

7.1 Prep Area

A suitable food processing area will be required in a full sized facility. During this research the food source was ground up to promote homogeneity of the resource and to discourage pests from entering the facility. A grinder capable of processing waste in the full sized facility could be too costly (capital and operational) for the provided benefits. The option to use a large scale grinder must be further evaluated before use in a large scale facility. The logistics of handling tonnes of waste were not considered in this research but the use of heavy machinery is anticipated.

7.2 Reactor Space

The construction of the reactor space would ideally consist of a material that is resistant to oxidation but based on the size of the required reactor cells this would most likely prove too expensive. Careful attention should be paid to maggot containment; any small crevices must be sealed. The only sealant used in this research that withstood the maggots was expanding insulation foam. The maggots destroyed acrylic caulking and silicone.

The walls of the reactor should be inclined at 30° to facilitate outward migration and fins should be attached spaced no more than 4 cm apart, their thickness is not relevant but more fins are expected to facilitate outward migration. The walls should be roughened to give the maggots a gripping surface. Aeration of the food pile must be provided either by mechanical mixing or via an aeration system. This will allow for higher maggot densities, resulting in a higher feed application flux and therefore a more efficient system operation. The use of a bulking agent may not be required if the feed is not ground.

The use of real-time monitoring equipment, O₂ sensors, humidity sensors and temperature sensors is highly recommended. Feedback based control of the water and heating systems will make the operation more efficient and cost effective. Operations should be run in batch mode: this will facilitate maintenance and cleaning operations and build facility resiliency by isolating negative effects to one production cycle.

7.3 Exit Ramp

This subsystem can be removed; the containment walls of the reactor vessel can be adapted to serve the same function as the exit ramp.

7.4 Collection System

The collection system piping can remain as four-inch ABS provided that a sufficient flow of water is present to prevent clogging by maggots. A solids removal system should be incorporated into the water reservoir to extend the life of the fluid and reduce wastewater production. The pump should be sized to maintain a fluid depth of at least 1 cm. The slope of the tubing should be sufficient to promote gravity drainage: in this research a slope of 1.5% was used.

7.5 Separator

The design of the separator may be subject to change given the number of maggots generated by a full sized facility. The piping diameter may need to be increased to prevent bottlenecks or more than one separator may need installation. It has been suggested that maggots do not like the light. In addition to providing a sufficient amount of water flow to force the maggots out of the separator, the use of lighting in the separation device should be explored to encourage maggots to leave the separation device.

7.6 Pupation Chamber

The pupation chamber must be kept at a suitable moisture level, 60% to 70%, to prevent desiccation of the pupa. It would also be practical if the medium grain size was smaller than the pupae but larger than the spiracle to allow mechanical sieving. The reason for the sieving is that the pupal casings that adults leave behind after they emerge are a food source for pests and could be a valuable product for industrial processes that require chitin. The removal of these casings will also become necessary as they build up over the course of time. The depth of the pupation medium must be kept at a depth between 15 to 20 centimetres. Wood chips appear to be the most successful pupation medium (Homes 2010).

7.7 Adult Space and Hatchery

The construction of the adult space must be done with special attention so that crevices are minimized and seams are sealed. This is vital to ensure that eggs are laid only the designated areas. Open floor space is important because many adults were observed to mate on the ground and cleaning up the dead adult carcasses will prevent other pests from entering the space. The use of plant life is recommended because males like to claim territories on leaves during mating. The adult space should have its own independent environmental controls and separate ventilation.

The hatchery should also have its own environmental controls to prevent the desiccation of eggs. The same attention paid to the minimization of seams and crevices in the adult space must also be used in the hatchery because any eggs laid outside of the intended location represent a loss in productivity and it will encourage other flies to lay eggs in those locations.

The use of disposable flutes is recommended. Research suggests that egg laying sites can become saturated with pheromones that will discourage females from laying their eggs there. The use of new cardboard flutes should prevent this occurrence.

7.8 Facility Design

The research conducted at the EWSWA landfill had mixed results. Although the values were obtained for key design parameters the methods used to sample the maggot number at any given time produced data with a high degree of variability. Contributing factors to this variability include the following:

- The maggot population within a given space is naturally highly variable, the number of live maggots changes constantly and is a function of the death rate, outward migration rate and the rate of incoming new maggots; and
- The nature of the sampling approach, using four 250 mL samples, could have missed some maggots or some maggots may have been too small to see and

therefore count. It was also observed that maggots changed location in the waste pile. Further investigations should reduce volume measurements to one dimension, the food pile depth while keeping the area constant.

Despite these setbacks the relationships between design parameters were characterized and a design process was elucidated. The primary design parameter was the average dry daily consumption rate (cDCRM) which allowed for the calculation of the application flux.

The conceptual design results reveal that a large facility size is required to process all of the daily waste amounts. In the EWSWA example case, the amount of waste that is diverted from burial in the landfill site is extremely low. The system may be better suited to agricultural applications where waste quantities and types result in shorter processing times allowing for higher diversion values. Despite this fact the use of BSF may still be a viable option for the production of a high quality protein animal feed. The estimated harvest rate of the system appears to be very high and the prepupae sell for \$1500 to \$2000 per ton.

The use of the maggot-exit ratio was limited or else non-existent and no conclusion could be made based on available data concerning its reliability at describing conditions in the reactor. Further research is needed determine if this ratio has any descriptive value.

Overall it would appear that BSF can be successfully cultivated year round at higher latitudes; however, under the specific research conditions explored the benefit exceeds the costs by a small margin. There are two possible ways to improve this situation. The first approach involves making improvements to the application flux – it must be higher than those attained in these trials.

This can be accomplished by increasing the number of maggots that can reside under a given area by increasing the depth of the resource and providing aeration; this will increase the magnitude of the application flux and reduce the area required to process

one ton of waste, boosting efficiencies to commercially viable levels by reducing building area requirements.

With the use of aeration maggots can be “stacked” on top of each other. Given that a single maggot is two centimeters long, it is conceivable that up to ten layers of maggots can fit into one square centimeter for a depth of twenty centimeters. Aeration may also increase the depths at which maggots can consume waste effectively.

The other approach is to improve the efficiency of resource consumption. The research was not conducted in an energy efficient setting. The greenhouse construction did not provide adequate insulation and maintaining suitable environmental conditions was difficult and costly. Full greenhouse construction is not recommended. The use of timers to control the resource delivery machinery was inefficient but had low capital costs. The use of sensors and software to control the resource delivery machinery will also improve the efficient use of resources which will in turn drive costs down.

7.9 Further Research

The area requirement for the facility stems from the assumption that only one layer of maggots can feed in a given area. This assumption was made to facilitate calculations because stratification was not observed to a great degree in the EWSWA facility during experiments. This is most likely the result of the lower oxygen availability at the deeper levels of the food resource. This is perhaps the most significant area for improvement; if oxygen can be delivered to these areas, stratification may become more common increasing the value of the application flux which would allow for smaller reactor sizes thereby decreasing the facility size.

Pre and post processing logistical issues require further research. If the facility is to be used for the processing of MSW, costs associated with source separation and transportation to the facility must be addressed. Costs associated with preserving the prepupae that are produced will also require further economic analysis to determine if the process is economically viable.

Another consideration is the type of waste being consumed. Fats and proteins can be difficult for BSF to consume and the experimental diet, restaurant waste, was high in these constituents. Small-scale waste consumption trials are recommended with the incoming waste stream to determine the average dry daily waste consumption rate prior to any system design.

The effects of temperature on the waste consumption rate should be further studied. The temperatures during these trials varied despite the attempts to control them. Carefully controlled studies done at different temperature would help determine the extent of temperature effects on the dry waste consumption rate and establish feeding kinetics.

Another potentially useful parameter is the amount of heat generated by a given volume of maggots. In the winter months this heat could be a helpful contributor to the design of heating systems. In the summer months this information would aid in the design of cooling systems.

In order to gain a more complete view of the process's sustainability, greenhouse gas contribution and potential adult fly attractants, the gases emitted by feeding maggots should be determined. An LCI characterized the flow of resources in the experiments but an LCA was not conducted.

The use of the trickling filter approach proved the most effective method of cultivating maggots but this could just be a consequence of the waste being ground up. If the feed stream is not ground this approach may lose its effectiveness. There were also problems with cleaning and maintenance issues that would be compounded in a full-scale facility. More experimentation is required to determine if this setup would be functional.

A constant consumption model was assumed to determine the average dry daily consumption rate. As previously stated, this is most likely not the case. A study that

considers all of the factors that affect the waste consumption rate would be useful for predictive purposes.

The nutritional requirements of the BSF larvae is an area for future research. The nutrients obtained by the larvae affect adult characteristics. In this research restaurant waste was the only diet fed to the developing larvae. Although this single diet source allowed for very good control measure, this lack of variability could have affected the reproductive success of the adults and other adult characteristics. Further research to determine when the larvae need changes to their diet would further aid the effective operation of a BSF waste management facility.

The most cost effective use of the produced resources should be further explored. Although the clearest use for the maggots is as a protein supplement in animal husbandry and aquaculture, the chemicals contained within the maggots could be used as an input in industrial production processes. The chitin leftover by the adults after they emerge may also have commercial value. The waste residue itself may also have use as a fertilizer and soil conditioner. It could be mixed with existing compost to add nitrogen; this would depend on the food source used by the maggots.

There are still many unknowns surrounding the adult BSF's mating behaviours. It is known that light plays a role and its intensity is an important factor. What is not known is the range of wavelengths that stimulate mating behaviours. Since electricity costs are a significant contributor to operational expenses, precise knowledge of the stimulating wavelengths could allow for the use of supplemental LED lighting which could result in significant power savings.

The optimal adult density for mating is also a variable that needs further study. In designs based on this research the optimal density was considered the highest observed value based on experiments. This assumption was necessary to complete calculations but it may not be the optimal density and since this value directly influences space requirements for the adult space, further study is necessary.

A means to accurately count adult numbers in real time would assist further research efforts into adult BSF behaviour. The attempted method used here proved impractical and unreliable. Instead, estimates were made from data collected during the mass balance experiments but this was done after the adults had completed their life stage.

The use of BSF presents an innovative and unique approach to waste solid waste management. With modest improvements, the process could generate a revenue stream, generate a value-added product and reduce the amount of organic waste that is disposed in landfills.

Vita Auctoris

Luis Alvarez was born in 1976 in San Miguel, El Salvador. He immigrated to Canada in 1983. He holds a bachelor's degree in Biology and Environmental Engineering. He is a professional engineer in Ontario. He is interested in environmental issues and hopes to pursue work in that field.